PERFORMANCE ANALYSIS OF CERTAIN COMPONENTS OF FIRE CONTROL EQUIPMENT FOR BOMBING AIRCRAFT

by

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Memorandum to: Captain W. H. Buracker

From: Dr. C. S. Draper

Date: September 4, 1946

Subject: Thesis Work of Lt.Comdr. Alan H. Yates
Lt.Comdr. Raymond J. Schneider
Lt.Comdr. I. Kinter Blough, Jr.

The officers listed above have recently submitted a Master's Thesis entitled:

"Performance Analysis of Certain Components of Fire Control Equipment for Bombing."

Intelligent attacks on a number of difficult experimental problems under unfavorable conditions resulted in a creditable thesis. A great deal of initiative and ingenuity was required to finish a considerable portion of the work originally laid out as the thesis project although delays in delivery of equipment seriously reduced the effective working time available. The officers involved are to be complimented on the ability they have displayed in their thesis work.

/s/ C. S. Draper
Chairman of Graduate Committee
Department of Aeronautical
Engineering

CSD:pm

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Submitted in Partial Fulfillment of the

Requirements for the Degree of

MASTER OF SCIENCE

from the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

1946

Thesis
Y5

August 24, 1946

Professor Joseph S. Newell,
Secretary of the Faculty,
Massachusetts Institute of Technology,
Cambridge, Massachusetts.

Dear Sir:

We hereby submit the enclosed thesis entitled "Performance Analysis of Certain Components of Fire Control Equipment for Bombing Aircraft" in partial fulfillment of the requirements for the degree of Master of Science from the Massachusetts Institute of Technology.

Respectfully yours,

ACKNOWLEDGMENT

The authors wish to take this opportunity to express gratitude and appreciation for the inspiration, assistance, and suggestions given them in their work, by Professor C. S. Draper of the Department of Aeronautical Engineering, who, in his capacity as advisor and instructor, constantly endeavored to bring theory and practice into closest agreement, and who was instrumental in providing the tested equipment; and by Mr. J. R. Rodgers of the Confidential Instruments Laboratory, who was particularly helpful in clarifying certain design intricacies of the mechanism tested.

TABLE OF CONTENTS

Summary

Chapter I — Introduction . . . . Pages 1 - 8

Chapter II — Range Input Channel of the Computer. Pages 9 - 18

Chapter III — Elevation and Azimuth Input Channel of the Computer . . . . Pages 19 - 26

Chapter IV — Altitude and Airspeed Input Channel of the Computer . . . . Page 27

Chapter V — Total-Correction Computation in the Computer . . . . Pages 28 - 33

Chapter VI — Conclusions and Recommendations. . . Pages 34 - 38

Appendix — Part (A) — Bibliography

Part (B) — Photographic Plates

Part (C) — Figures

Part (D) — Tables

LIST OF PHOTOGRAPHIC PLATES

I Mechanical Oscillator.

II Back View of Computer.

III Front View of Computer.

IV Axis Converter and Potentiometer Resolver.

V Breadboard Layout of Input Terminals.

LIST OF FIGURES

1 - Schematic Diagram of the Central Fire Control System.

2 - The Computer Servomechanisms.

3 - Potentiometer Range Servomechanism, Simplified.

4 - Cathode Ray Oscilloscope for Frequency Response Studies, Determination of Amplitude and Phase Lag.

5 - Range Output Response Curves, Magnitude and Phase.

6 - Transfer Locus of Range Channel.

7 - Velocity Error due to Range Rate.

8 - Stadiametric Ranging.

9 - Schematic Circuit for Determination of Range Sensitivity.

10 - Computer Range Channel Sensitivity versus Present Range.

11 - Schematic Diagram Showing Operation of Synchro Azimuth Servomechanism and the use of Cathode Ray Oscilloscope for Frequency Response Studies.

12 - Transfer Locus of Azimuth Channel.

13 - Transfer Locus of Elevation Channel.

14 - Azimuth Output Response Curves, Magnitude and Phase.

15 - Elevation Output Response Curves, Magnitude and Phase.

16 - Calibration Curve for Velocity Studies.

17 - Steady State Error for Constant Angular Rates, Azimuth.

18 - Lead Error introduced due to Error in True Azimuth sent to Lead Computer.

19 - Lead Computation Schematic.

20 - Azimuth-Total Correction versus Solution Time.

21 - Elevation Total-Correction versus Solution Time.

LIST OF TABLES

I - Frequency Analysis Data for Range Channel.

II - Data for Velocity Study of Range Channel.

III - Range Sensitivity Data.

IV - Maximum Range-Rate Inputs at Various Ranges.

V - Frequency Response Study for the Azimuth Channel.

VI - Frequency Response Study for the Elevation Channel.

VII - Steady State Error for Constant Angular Rotation.

VIII - Calibration Table for Cathode Ray Oscilloscope.

IX - Total-Correction Computation Data.

SUMMARY

This paper deals with the 2CH1C1 computer used in the Central Station Fire Control System as installed in the U. S. Army Air Forces' heavy bomber, type B-29. Essentially, the computer consists of six servomechanisms which position gears, "waggle sticks", and finally four differential synchro-generators, the latter modifying signals sent from the sighting station for ballistic and lead corrections developed within the computer and transmitting the resultant gun orders to the firing station.

In their report the authors have presented results of detailed tests on three of the servomechanism channels, the Range Input Channel, the Azimuth Input Channel, and the Elevation Input Channel. Tests were made chiefly from a transfer function viewpoint. Certain static sensitivities within the equipment were measured. The Altitude and Airspeed Input Channel and the Azimuth and Elevation Total-Correction Channels were not tested in thorough detail since certain essential units of the system were not available. However, other pertinent information on these channels is presented insofar as experimental determination was possible.

Briefly, the chief results and conclusions may be listed as follows:

1) The servomechanism channels are properly damped and stable but have a rather low resonant frequency.

2) Maximum speed of follow-up in these channels, as limited by the driving motors, is too slow to handle modern, high-velocity problems.

3) Solution time is relatively long, and is approximately proportional to the amount of total correction required.

4) The overall computer performance is limited by the contactor or discontinuous type of servomechanisms used. These function as proportional type servos, and as such have steady state velocity errors.

CHAPTER I

INTRODUCTION

With the advent of large bomber-type aircraft, such as the Air Forces' B-29, and the necessity for protecting these aircraft from enemy fighters, application of fire control principles to aircraft armament has become feasible and necessary. Current applications of these principles follow two distinct lines. They are: (1) The disturbed reticle type of sight, such as the Mk. 18 or the A-1, the latter described in detail in *Detailed Theory and Computations for the A-1 Sight for the Control of Gunfire from Fixed Guns, Rocketfire, and Bombing from Aircraft* by Dr. C. S. Draper. This type of system, in brief, involves a line of sight kept on the target via a reticle which is offset from the gun line by the amount of correction necessary to insure that the projectiles hit the target. (2) The fixed reticle type of sight, which employs a computer to offset the guns for lead corrections, such as the General Electric system used in the B-29 aircraft. The latter installation is described in U. S. Army Technical Order, 11-70A-1, *The Central Station Fire Control System*.

The present problem involves the fixed reticle type of gun director. The system that is used in the Air Forces' B-29 aircraft resembles closely that which is used aboard modern ships of the Navy, and, as far as is known, represents the first time that the type of system has been applied to aircraft fire control. It is referred to as the fixed reticle, central station fire control system, and in general, consists of: (1) A director station in which a line of sight is established to the target and is kept there by proper tracking in accordance with the target motion. The director has a fixed tracking index or reticle which moves integrally with it. (2) A computing station to which information from the director is sent to be properly combined with such additional data as is necessary to compute a correct gun order signal. (3) A firing station, or group of such stations which follow the gun orders as developed by the director and the computer. Modern central station fire control systems utilize servomechanism technique to render the operation of the system almost completely automatic from the director through to the firing station. In these systems the three basic divisions become more emphasized.

In the discussion to follow, as well as in the subsequent chapters, the terminology used is due to the U. S. Army Technical Order 11-70A-1 previously cited, with the additions that the terms "synchro" and "Selsyn" are used interchangeably, and "servomechanism" is used to indicate a follow-up system. In the diagrams, dotted lines are used to indicate mechanical linkages, and unless otherwise noted full lines are used to show electrical wiring, circuits, constants, and units.

Fig. 1 is a schematic diagram of the central station fire control system which is used in the B-29 type aircraft. The figure shows in the blocks the three divisions typical of this fire control system. It will be noted that each of the divisions, the sighting station, the computer, and the turret, are mechanically independent; i.e., they are connected only electrically. In the sighting station the gunner generates an electric signal in the synchro generator indicating position by turning the sight head. Here, as in the turret, the signal system is composed of one and 31 speed synchros to provide the necessary accuracy. The signal appears as a voltage in the computer differential synchro, and is there modified by the amount of the correction. From the rotor of the differential synchro the signal goes to the stator of the turret synchro control transformer where it may generate an error signal that will align the guns to hit the target. Fig. 1 shows only one plane of motion for the sighting station and the turret drive. The motion in the other plane, either azimuth or elevation is obtained by another exactly similar system. However, both the azimuth and elevation servomechanisms use the same computer.

The servomechanism driving the turret is characterized by the amplidyne and is entirely electric. Briefly, supposing the computer to be turned off and the synchro differential rotors to be aligned with their stators; then a signal voltage is sent from the synchro generators directly to the synchro control transformer in the turret. The turret is geared to the rotor of the control transformer. Suppose that the turret is in slight misalignment with the rotor of the generator. Then an error voltage appears across the control transformer rotor terminals. This voltage is transmitted to the servo-amplifier which applies rectification and power amplification to it and uses the resulting current which is still proportional to error in the amplidyne control fields. The amplidyne is the final power amplifier for the servomechanism and sends a controlled amount of current to the turret drive motor armature.

The motor has a separately excited field; hence, the torque and speed are almost entirely dependent upon the armature current. When the motor receives its current it turns in a direction to align the turret parallel with the direction of the synchro generator rotor, thus cancelling out the error voltage in the control transformer rotor. The turret drive servomechanism has characteristics which may be made almost anything within the limits of a position control servomechanism. Depending upon the design of the servo amplifier, the amplidyne, and the turret drive motor, it may vary from almost critically damped to absolutely unstable. Supposedly the system will be designed to have characteristics most desirable in its application.

It is important to note here, as indicated by Fig. 1, that there is no feedback or coercion between the turret and the computer or the sighting station. The aximuth and elevation indications of the guns are fed to the computer from the differential synchros in the computer; hence are not necessarily the actual gun position. On the other hand, the sighting station and the computer are intimately related by the lead gyroscopes and the ranging device. This peculiarity makes it possible to study the computer independently of the turret, but not of the sighting station.

In particular, the problems at hand deal with the computer of Central station fire control system that is used in the Air Forces' B-29. The computer involves six servomechanisms. Actual computation is done mechanically when the servo motors position the various gears, differentials, worm gears, and "waggle sticks". Fig. 1 indicates that the computer obtains its inputs from several different sources. The inputs that actuate the six servo motors are:

(1) and (2) Azimuth and elevation computed gun position from the differential synchro rotors.

(3) Range from the range potentiometer positioned by the gunner at his sighting station.

(4) True air speed, density altitude obtained as a single controlled voltage from the handset unit available in the B-29 to the navigator.

(5) and (6) Relative velocity of the target with respect to the gunner's aircraft modified by projectile time of flight to give lead; furnished by two gyros in the sighting station and a time-of-flight electrical network in the computer.

Fig. 2 is a schematic block diagram of the computer which shows the essentials of the six servomechanisms and their mechanical linkages. Plate IV indicates some of the electrical and mechanical details of the potentiometer resolver and the axis converter which together afford the adjustments to the total correction motors. Plates II and III give front and back views of the computer. Here salient visible points of interest have been labeled.

The operation of the computer is best described by taking two examples. In the first case, suppose, for example, that conditions are set as follows: The sighting head at the sighting station is started moving in azimuth, but not in elevation. No range is being put in. The altitude and airspeed remain constant. In other words, only the lateral component of lead correction is being considered. The angular velocity of the sight head causes the azimuth gyro to precess, closing a contact. This, in turn, energizes two relays causing the azimuth total correction motor to turn in the proper direction. The total correction motor is the servo drive for the rotors of the differential selsyns (both 1 and 31 speed). Necessary feedback occurs since the total correction motor also drives the axis converter. The axis converter positions the potentiometer resolver, which sets up a voltage to establish a current in the gyro erecting coils to precess the gyro off the contacts. The latter conditions hold constant as long as the sight head moves at a continuous rate. That is, the gyro erecting coil has just sufficient current to keep the gyro off the contact. In positioning the rotor of the differential synchro, the total correction motor, through its gears, has modified the signal from the sighting station by the amount necessary for lead correction.

As a second example, consider that the sight head is being held steady in both azimuth and elevation, that altitude and airspeed are constant, but that the gunner is ranging on a target. It is presumed that the range servo channel in the computer is matching perfectly the range signal sent from the sighting station. Through a mechanical linkage which converts rotary to lateral motion (the pantograph and waggle sticks) the potentiometer resolver is again positioned away from neutral. This action again sets up a voltage to drive current through the gyro erecting coils. Since, in this case, there is no lead correction, and no torque due to angular velocity, there is no torque to counterbalance the torque set up by the erecting coil. Therefore, the erecting coil torque causes the gyro to precess and close the contact energizing the total correction motors through their relays. The correction motors then reposition the potentiometer resolver through the axis converter until the gyro erecting coils receive no more current. And, as before, the total correction motor positions the rotors of the differential synchros, which in turn govern the gun position.

From the figures, plates, and the previous discussion, several noteworthy facts may be set down pertaining to the computer and its servomechanisms. These are:

(1) The range, altitude and air speed, and azimuth and elevation differential synchro positioning servos are of the potentiometer type.

(2) The azimuth and elevation correct gun position input servos are of the synchro type.

(3) All six of the servomechanisms are of the so-called contactor type. That is, the error signal is amplified and then used to open and close relays which latter actually supply the driving current to the servo motor.

(4) The computer and sighting station are intimately related by the lead computing gyros in the sighting station in that all corrections generated by the computer must go to the sighting station before becoming gun orders.

As originally set up, it was proposed to investigate all six of the servomechanisms in the computer from the Transfer Locus viewpoint as presented by Dr. A. C. Hall in his _Analysis and Synthesis of Linear Servomechanisms_. With this viewpoint in mind, of course it is assumed that the contactor type of servomechanism will behave like a continuous one. Further, it was decided to obtain as many static sensitivities as possible. Then, if time permitted, the transient response to step functions of the servomechanisms were to be investigated as suggested by Dr. C. S. Draper in his Instrument Analysis and by Dr. G. S. Brown in Transient Behaviour and Design of Servomechanisms. With the above characteristics known, then the ability of the computer to perform its function can be predicted in advance. It was then proposed to set up a synthetic problem for the computer, put it in to the machinery, and observe the accuracy of the results appearing at the output of the differential synchro rotor. Most of the above outlined program necessitates the use of a sighting station. Unfortunately, that did not become available. Hence, the procedure had to be modified to include studies of only three of the servo channels, those of azimuth, elevation, and range; and certain characteristics of the total correction motors.

In the subsequent presentation of results the notation used is that of Drs. Draper, Brown, and Hall as given in their previously cited works. The sinusoidal oscillator, shown in Plate I, was built for this and previous experiments by the authors. The computer dealt with is the so-called "single parallax" variety, Model 2CH1C1, computing gun orders for only one firing station.

CHAPTER II

RANGE INPUT CHANNEL OF THE COMPUTER

Range input to the computer mechanism is through an electrical servomechanism, potentiometer-controlled. Measurement of range is made at the sight head with a stadiametric type reticle, adjustment of which to span the wing of a target airplane, sets the controlling potentiometer to the proper value for the range measured. The relay-contactor type servomechanism in the computer responds to this signal and drives the measured value of range into the mechanism.

The analysis of the range input channel is made with three major aims:

1) Investigation of the general performance of the basic servomechanism as such, including transfer locus and velocity error studies.

2) Experimental determination of the static input to output sensitivity of the channel.

3) Investigation into the maximum range rates to which the system can respond.

In the detailed discussion which follows, these three topics are kept separate as far as possible, though a certain amount of overlap in scope is unavoidable.

The servo system was investigated through application of a sinusoidal forcing function on the input potentiometer. Measurement of input position (θ_i) and output position (θ_o) were made simultaneously in both magnitude and phase by use of a cathode ray oscilloscope.

A simplified layout of the range channel is shown in Fig. 3. This figure further shows the additional circuit required to introduce the cathode ray oscilloscope into the system so as to properly balance out any fixed voltage levels, since θ_i and θ_o were both desired as functions varying sinusoidally about a zero reference level.

Use of the cathode ray oscilloscope for measurement of the two quantities, θ_i and θ_o, with their phase difference is clearly indicated in Fig. 4. System error, which will be written as E, with $E = \theta_i - \theta_o$, might have been measured instead of θ_i or θ_o and this technique is used of necessity in later parts of the work. The calculation of vector E is easily done by vector subtraction of θ_o from θ_i and in the usual case E is found to be leading the input, θ_i. The ratio θ_o/E, defined as the transfer function of a servo system, is found by vector division.

The zero position of θ_i was chosen as 375 yards range and the amplitude of oscillation about this value was set at 25 yards. It was evident from analysis, as will be brought out in a later discussion, that the range channel was not linear throughout its range of 250 to 1500 yards, but an investigation of the servo performance in one section of its range was considered sufficient to show general performance. The frequency of input was varied from about 0.15 to 3.7 cycles per second, this variation covering the usable range of the device.

Data obtained in this investigation is recorded in Table I, which also includes the additional items calculated as necessary to permit plotting of the standard transfer-locus curves developed by Dr.

A. C. Hall in his paper entitled, "The Analysis and Synthesis of Linear Servomechanisms". The ratio of output to input, θ_o/θ_i, with magnitude and phase plotted separately, is shown in Fig. 5. The transfer-locus of the system, θ_o/E, is plotted on polar coordinates in standard servomechanism fashion and presented in Fig. 6. These two plots illustrate the performance of the system and bring out all salient characteristics.

It must be noted that, while the transfer-locus method of servomechanism analysis as developed by Dr. Hall in the reference previously cited was primarily directed towards continuous systems, its application to a discontinuous system, relay-contactor controlled type in this case, results in a locus plot quite similar to what might be expected of a continuous system. The individual discontinuities are small with reference to the overall operating region and are effectively smoothed by the mass and frictional damping of the mechanical portions of the system, thus permitting a general analysis of this system along the well-developed pattern of continuous servomechanisms.

The transfer-locus, Fig. 6, shows the system to have the general form of a proportional servo throughout its operating region. For this type of servo the characteristic equation may be written as:

$$J_o\ddot{\theta}_o + f_o\dot{\theta}_o + k\theta_o = k\theta_i$$

where

J_o is the effective mass of the system reflected to the output shaft;

f_o is the effective viscous damping of the system reflected to the output shaft;

k is the proportionality factor or gain constant of the system.

This characteristic equation may be written in non-dimensional form as:

$$\ddot{\theta}_o + 2\zeta\omega_n\dot{\theta}_o + \omega_n^2\theta_o = \omega_n^2\theta_i$$

where ω_n is the natural frequency of the system $= \sqrt{\frac{k}{J_o}}$

and ζ is the damping constant of the system $= \dfrac{f_o}{2\sqrt{kJ_o}}$

Assuming that the system operates as a simple proportional servo then, it obeys the laws of the 2nd order differential equation. From Fig. 5, of θ_o/θ_i, the maximum value of the resonance function, that is, $\theta_o/\theta_{i(max)} = \mu(max)$, is found to be 1.21 and this maximum occurs at a forced frequency of 0.95 cycles per second. Utilizing the curves of Plates 6 and 12 from the pamphlet entitled "Instrument Analysis", by Prof. C. S. Draper and Walter McKay, entering with this resonance data, the value of the damping constant, ζ, can be determined and also the value of the frequency ratio, $\beta = \frac{\omega}{\omega n}$, at which resonance occurs. ζ is thus found to be 0.445 and $\beta_{(max)}$ to be 0.80. The resonant frequency of the servo may then be calculated as $\frac{0.95}{0.80} = 1.187$ cycles/second. This value of natural frequency is somewhat low for a good servomechanism though the value of ζ is within the range of usual engineering practice, 0.4 to 0.7.

Actually, the transfer-locus rises above the negative imaginary axis on the polar plot, Fig. 6, indicating the existence of some higher order effects than written in the simple proportional equation and this existence is verified at once by the plot of the phase angle of θ_o

versus frequency, Fig. 5, which differs considerably from the usual form for a second order equation. These higher order effects are useful in that they tend to improve the response of the mechanism, particularly in reducing the value of error at velocity inputs. Such an input is the usual case for the range servo since it represents a range rate input.

Further study into the performance and analysis of the range input channel was made through a series of velocity inputs. The range input potentiometer was driven at various angular rates and the error of the output in following its input was measured on a calibrated cathode ray oscilloscope. The non-linearity of the system was neglected and the input range rate was computed on the basis of the time to close range by 800 yards, in the scale region 1200 yards to 400 yards. Error was measured in volts and conversion from volts to yards is possible through use of the range sensitivity curve later obtained. As a quantitative measure this portion of the work is somewhat inaccurate by reason of the non-linearity of the system and its varying sensitivity from maximum to minimum range indication. Qualitatively, however, the results indicate the order of error at various range rate inputs, and give an exact value of the maximum error to be expected.

Data was taken for range rates from 37 to 333 yards per second, corresponding to closing attacks from 75 to 681 miles per hour. Error in volts at the input to the servo amplifier corresponding to the various range rates is recorded in Table II. The plot of this error versus range rate in miles per hour is given in Fig. 7. This plot is essentially linear. Again returning to the assumption previously made, that the mechanism performance equation is of second order, that is, of the form:

$$\ddot{\theta}_o + 2\zeta\omega_n\dot{\theta}_o + \omega_n^2\theta_o = \omega_n^2\theta_i ,$$

the velocity error for any angular rate input can be theoretically calculated, neglecting initial transients, as:

$$E_v = \frac{2\zeta\dot{\theta}_i}{\omega_n}$$

Derivation of this steady state error term may be found on pages 11-12 of the paper entitled, "Transient Behaviour and Design of Servomechanisms", by Dr. Gordon S. Brown. This is a linear equation and its plot should pass through the origin at zero input velocity. The experimental data shows the proper linear relationship, but does not pass through the origin. The value of error at zero velocity input is then the minimum error to which the channel will respond to its input and is of the order of the noise or hash level in the system.

Experimental evaluation of the input to output sensitivity of the range channel was made at the computer. Overall sensitivity of the range system from the sight to the computer should obviously be unity, that is, a given range as measured at the sight reticle must be eventually transmitted to the computer correctly within such mechanical, electrical, and computational limits of accuracy as may be necessary.

A simple stadiametric ranging unit measures range as a function of a base length and an angle. The output of such a system as shown in Fig. 8 may be written as:

$R = \frac{n}{\tan \theta}$ where n = base length, ½ wing span in this case

θ = angle subtended at measuring station by the base length

R = range in units of the base length.

As θ is substantially the input to the ranging potentiometer which the computer must follow, it is preferable to write the previous equation as: $\theta = \tan^{-1} \frac{n}{R}$. The equation may be further transformed to a logarithmic form as:

$$\theta = \tan^{-1} (\text{antilog} (\log n - \log R))$$

Actually, because of mechanical limitations in construction of the reticle forming slots in the sight unit of this system, it was found desirable to further modify the input term R to a function of R other than the reciprocal as called for in the previous equations. The final result is then written as:

$$\theta = \tan^{-1} (\text{antilog} (\log n + \log f(R)))$$

This somewhat complicated relationship is generated at the sight and delivered as the input angle θ to the range transmitting potentiometer through a non-circular gear train. θ_i is then answered at the computer through a matching set of non-linear gears on the θ_o potentiometer, the net result being delivery of range values from sight to computer at a sensitivity of unity. Both input and output potentiometers are themselves linear within manufacturing tolerances.

Sensitivity at the computer was measured in terms of yards output range per volt input from the error measuring θ_i and θ_o potentiometers. The method used to measure this sensitivity is explained in conjunction with the circuit connections as shown in Fig. 9. Certain ranges were set on each of two potentiometers connected so as to alternate as the θ_i input by the throw of a double throw single pole switch. These ranges corresponded to adjacent scribed values on the computer internal range scale, thus setting a mean range and a range increment between the potentiometers. The computer was then allowed to follow one of the input signals to its set range. Direct current input to the range follow-up motor was cut off and the SPDT switch thrown to the other potentiometer. Error voltage developed for the known range increment was then read on a vacuum tube voltmeter, Hewlett Packard type 400A. The sensitivity thus obtained, labeled S_{TR}, was computed as $\frac{\Delta R}{\Delta E}$ in units of yards/volt and defined as existing at the mean range between the two ranges set on the θ_i potentiometers. Residual errors were also measured, these being the error in volts still existing after the computer had matched the input signal as closely as possible. These errors correspond to the hash or noise level previously mentioned and are the minimum voltage errors required by the range channel for any response. Sensitivity data thus compiled is presented in Table III, and a plot of S_{TR} versus mean range is given in Fig. 10. This plot shows an almost linear increase of range sensitivity from minimum to maximum range limits of the computer. Sensitivity increases from about 5 yards/volt at a minimum range to 38 yards/volt at maximum range. This agrees qualitatively with the theoretical equation previously written for input to the transmitting potentiometer, which plots generally as an arc-tangent curve and is substantially linear in the early part of its range.

From the velocity study previously discussed and in conjunction with the sensitivity curve of Fig. 10, it is possible to calculate the maximum errors in range likely to be present at any given range rate. The largest error voltage measured was 1.100 volts at 681 miles per hour and if this error occurred near maximum range where the sensitivity is approximately 35 yards/volt, the range error would be only about 38.5 yards. Generally, the range error due to range rate is considerably less than this maximum. Hence, it is clear that velocity error caused by the incoming range rate is not a serious cause of computational error. However, analysis of the maximum rate of range input, which is limited by the maximum speed of the range follow-up motor does show some serious deficiencies.

The actual relation between input range R and the angle α, expressed in radians, of the rotation of the motor output gear from some suitably chosen initial position, is given by the following formula:

$$\frac{.406}{41.06\pi}\alpha = .6242 \log_{10}\frac{(R+110)}{217} = .2711 \log_e \frac{(R+110)}{217}$$

taken from a pamphlet entitled "Ranging in Defense of the B-29 Against Nose Attacks" by [illegible]. C. Lewis.

Taking the time derivative of this equation:

$$\frac{.406}{41.06\pi}\frac{d\alpha}{dt} = \frac{.2711}{(R-110)}\frac{dR}{dt} \qquad \text{or}$$

$$\frac{dR}{dt} = .001216\ r\ (R-110)$$

where r = revolutions per minute of the motor output gear

$$= \frac{60}{2\pi}\frac{d\alpha}{dt}$$ and is a maximum of 250 revolutions per minute.

From this formula a table can be computed of the maximum range rate possible for the computer to follow at various input ranges. Such a computation yields the data presented in Table IV. This table shows that at ranges less than 1000 yards the computer cannot follow a range rate of 700 miles per hour, which value might easily be experienced in a nose attack. As the range closes to 500 yards, which is the usual effective-open-fire range for an attacking fighter, the maximum input range rate is only 378 miles per hour. This analysis clearly shows that the greatest limitation on the accuracy of the range input is the maximum speed of the range follow-up motor. For satisfactory range input in an attack problem at speeds of standard service aircraft the follow-up motor should run at about twice its present rated speed.

Recapitulation of the results obtained in the analysis of the Range Input Channel may be made as follows:

(1) The Range Input servomechanism approximates the simple proportional type, with a natural frequency of 1.187 cycles/second and a damping ratio of 0.445. Maximum value of the resonance function, θ_o/θ_i, is 1.20.

(2) Velocity errors in the system result in a maximum error in range of about 40 yards at a 700 mile per hour closing range rate.

(3) Noise or hash level in the error channel averages about 0.5 volts, equivalent to about 2.5 yards at minimum range and increasing to about 19.0 yards at maximum range.

(4) Maximum range rates to which the channel can respond by reason of the follow-up motor speed limitation become increasingly unsatisfactory below 1000 yards present range, until at ranges below 500 yards, the system is unable to meet range rate requirements in defense against most normal attacks.

CHAPTER III

ELEVATION AND AZIMUTH INPUT CHANNEL OF THE COMPUTER

The elevation and azimuth channels to the computer are electro-mechanical servomechanisms. They are selsyn type follow-up systems. In the computing system, the selsyn signals from the sighting station are introduced into differential selsyns in the computer which alter the signal by the amount of the total correction. The signals are then sent to the control transformers on the turret and from there to the servo amplifier and finally position the guns to their correct position. The azimuth and elevation gun position systems also contain control transformers in the computer (only one speed selsyns used) which are connected in parallel with those on the turret. Thus, the corrected gun signal - which is fed to the azimuth and elevation turret selsyns - is also fed to selsyns in the computer. Since the computer's azimuth and elevation channels are almost identical, only the azimuth function will be described. Investigations were conducted on both channels.

The rotor winding of the azimuth selsyn control transformer in the computer is connected to an amplifier in the computer. The output of this amplifier actuates a relay system which in turn supplies power to a small follow-up motor. This causes a shaft to rotate, which gives the computer the correct value of gun azimuth, as well as driving the rotor of the selsyn control transformer.

In order to understand the basic principles of operation, as well as the methods used in measuring, a simplified computer gun-position system is shown in Figure 11. Assume, for example, that the sight and, hence, the 1-speed selsyn rotor on the sighting station are turned five degrees in a clockwise direction. A voltage will appear across the rotor winding of the computer control transformer. This voltage is applied to the input transformer of the amplifier. The polarity of this voltage is such as to make the left hand grid positive and the right hand grid negative during the half cycle that the tube is conducting (plates are positive). The left-hand grid will allow current to flow in the left side of the tube, while the right-hand side is cut off. This will cause the operating coil of relay R-CW to become energized, while the operating coil of R-CCW remains de-energized. When relay R-CW picks up it closes its normally-open R-CW contact, and opens its normally-closed R-CW contact. This applies positive 27 volts to terminal (B) of the motor, and connects terminal (A) to ground, thus causing the motor to rotate in such a direction as to drive the azimuth gun-position shaft and the selsyn control transformer rotor in a clockwise direction. The motor will continue to drive until the voltage across the control transformer rotor winding becomes zero.

The investigation was conducted to study the static and dynamic qualities of the channel up to the computer azimuth shaft, to determine the magnitude of errors introduced into the lead computing stage by the selsyn transmitting system.

Two studies were made:

(1) A study of the response to a sinusoidal forcing function over a range of frequencies. ($\theta_i = A \sin \omega t$).

(2) A study of the steady state error at constant speeds of rotation.

Measure of magnitude and phase of the error signal was made by use of the Cathode Ray Oscilloscope. The wiring necessary to introduce the scope into the control circuit is shown in Fig. 11.

In this case, as mentioned in Chapter II, error was measured rather than the output, θ_o. Error (E) and input (θ_i) were measured. Phase difference and amplitude were determined as indicated in Figure 4. This information permits a vector plot of θ_i/E. Data is found in Tables V and VI.

Then

$$\frac{\theta_o}{E} \triangleq KG(S)$$

$$\theta_i - \theta_o = E$$

$$\theta_o = \theta_i - E$$

$$\frac{\theta_i - E}{E} = KG(S)$$

$$\frac{\theta_i}{E} = KG(S) + 1 = \frac{\theta_o}{E} + 1$$

or

$$\frac{\theta_o}{E} = \frac{\theta_i}{E} - 1$$

The plot of θ_o/E may thus be obtained by moving the θ_i/E plot to the left a distance of one unit. Transfer loci plots of the azimuth and elevation response are shown in Figures 12 and 13. These show that these systems, even though they are contactor servos, follow the general plan of a good proportional servomechanism.

From this plot (θ_o/E) and data obtained in the Table for θ_i/E, data for θ_o/θ_i may be obtained since

$$\frac{\theta_o/E}{\theta_i/E} = \theta_o/\theta_i$$

Phase angle for θ_o/θ_i is equal to the difference in the phase angle of θ_o/E and θ_i/E. These values are tabulated in Tables V and VI.

Plots of θ_o/θ_i for the azimuth and elevation channels are shown in Figures 14 and 15.

The velocity study was conducted by driving the selsyn generator on the input at a constant speed. The elevation and azimuth channels gave similar results, and data obtained on both are incorporated into one Table and plotted as one curve. Measurements were made on the Cathode Ray Oscilloscope in a manner similar to the sinusoidal study. The error voltage was measured as a linear distance on the oscilloscope screen. A subsequent investigation permitted this linear distance to be calibrated as degrees or mils of error. This was done by blocking the computer output shaft and measuring the oscilloscope displacement for known errors.

The data for these investigations is tabulated in Tables VII and VIII and the curves of calibration and angular error are shown in Figures 16 and 17.

The analysis of the above mentioned data yields values for the ζ and ω_n of the elevation and azimuth channels. Use was again made of the references and formulas mentioned in Chapter II.

Elevation

μ max = 1.12 at ω_f = 1.47 cycles/sec
(from Fig. 15)

$\zeta = .51$

$\beta = .7$

$$\beta = \frac{\omega_f}{\omega_n}$$

$$.7 = \frac{1.47}{\omega_n}$$

ω_n = 2.1 cycles/sec

Azimuth

$$\mu_{max} = 1.17 \text{ at } \omega_r = 1.28$$

(from Fig. 14)

$$\beta = .76$$

$$\zeta = .47$$

$$.76 = \frac{1.28}{\omega_n}$$

$$\omega_n = 1.69$$

These values for ζ are within the range of good engineering practice, 0.4 to 0.7. The resonant frequency is somewhat low for usual engineering practice, but in a gun directing system this type of response is desirable. Oscillation of the sight due to vibration of the aircraft or movement by the gunner at high frequencies are smoothed out by the poor response of the computer at these frequencies. The small value of μ at the lower frequencies is also desirable.

Investigations conducted by the Department of Physics, University of New Mexico (Tests Related to the Defense and Tactical Use of the B-29) tend to prove that the overall system (turret and sight head included) show a much larger value of μ , a smaller value for ζ , and a higher resonant frequency.

The steady state error introduced into the lead computing system varies almost linearly with the angular rate of the sight. The size of the errors, though large, do not introduce much error in the actual final computed lead. Also, the azimuth and elevation of the turret follows the signal introduced by the sight more closely since the turret is fitted with both one-speed and 31-speed control transformers.

The reference noted above (Tests Related to the Defense and Tactical Use of the B-29) draws attention to the fact that with the overall system, the gun position error at constant angular rates is greater with the computer linked in the system than with the computer by-passed and out. This error varies with the azimuth. Obviously, this larger error increment is introduced by the computer. Part of the error is due to the error in the azimuth signal received by the computing system at an angular rate.

To determine the magnitude of the lead error in azimuth introduced by the incorrect azimuth signal to the computing system, a parallax of forty feet is assumed. This is the approximate value of the largest parallax found in the system. The magnitude of the error is further dependent upon range, relative velocity of the target and the azimuth of the target. Curves showing representative values of this error are presented in Figure 18. The following development was used to determine these values.

V = Speed of the target perpendicular to the line of sight and relative to the bombing aircraft.

R = True range in feet.

ϕ = True azimuth angle off the bow.

L_p = Lead angle due to parallax.

E_ϕ = Error in azimuth angle sent to the computing system.

E_1 = Error in lead angle due to error in azimuth angle received by the computing system.

ω = Angular rate of rotation of the sight.

$\omega = \frac{V}{R}$

E_ϕ may be determined from Fig. 17 by entering with ω as an argument.

Then by the law of sines applied to the simple parallax diagram

$$\frac{\sin L_p}{40} = \frac{\sin \phi}{R}$$

$$\frac{\sin (L_p + E_L)}{40} = \frac{\sin (\phi + E_\phi)}{R}$$

L_p and E_L are small angles so

$$L_p = \sin L_p$$

$$L_p + E_L = \sin (L_p + E_L)$$

$$L_p + E_L = \frac{40}{R} \sin (\phi + E_\phi)$$

$$L_p = \frac{40}{R} \sin \phi$$

$$|E_L| = \frac{40}{R} \left[\sin (\phi + E_\phi) - \sin \phi\right]$$

$$= \frac{40}{R} (\sin \phi \cos E_\phi + \cos \phi \sin E_\phi - \sin \phi)$$

$$= \frac{40}{R} \left[\cos \phi \sin E_\phi + \sin \phi (\cos E_\phi - 1)\right]$$

$$\cos E_\phi \cong 1$$

$$|E_L| = \frac{40}{R} \cos \phi \sin E_\phi$$

This development shows that while the error received by the computing system may be appreciable, the final error in lead applied to the gun position signal is small. However, it explains the origin of part of lead error introduced by the computer and demonstrates the reason for its variation with azimuth.

The results obtained in the Azimuth and Elevation Channels may be summarized as follows:

(1) The Azimuth and Elevation servomechanisms approximate a simple proportional type, with a natural frequency of 2.1 cycles per second in the azimuth channel and 1.69 in the elevation channel. Values of the damping ratio were in the range of good engineering practice; 0.51 for the azimuth channel, 0.47 for the elevation.

The response of the overall system appears to be poorer than the computer alone, and while the computer is partially responsible for any system lag, its individual response is good and is effective in smoothing out sight head oscillations.

(2) The use of the one-speed selsyn channel alone in the computer results in poorer matching with the positioning signal than at the guns, and introduces an appreciable error into the computing system when the sight head is rotating. This signal error results in a small error in computed lead.

CHAPTER IV

ALTITUDE AND AIRSPEED INPUT CHANNEL OF THE COMPUTER

Altitude and Airspeed input to the computer mechanism is through an electrical servomechanism potentiometer-controlled, very similar to the range unit. Settings of indicated air speed, temperature, and barometric altitude are made on the Altitude and Air Speed Handset Unit located in the navigator's compartment of the B-29. These three inputs are combined at the Handset Unit into a single function representing true air speed and density altitude by a complicated network made up of fifteen potentiometers. The final output function is transmitted as a voltage signal to a receiving potentiometer located in the computer. The amplifier and follow-up system reacts to error voltage existing between input signal and receiver potentiometer in the same manner as the range channel servo.

No Handset Unit was available and no data could be located to permit investigation of this channel for a determination of sensitivity. Specific data was not taken for this channel but observations were made of its speed of response. The performance is extremely slow and this channel is by far the worst servomechanism of the computer.

Instructions as set forth in the operational manual for the system are to make settings on the Handset Unit sufficiently in advance of a firing problem to permit at least five seconds elapsed time for the follow-up system to react.

This channel is obviously a weak link in the computer input system but has been tolerated on the assumption that airspeed and altitude changes will be negligible during normal firing problems.

CHAPTER V

TOTAL CORRECTION COMPUTATION IN THE COMPUTER

The final output of the computer consists of a total correction applied mechanically to a differential selsyn generator. The firing station then follows the sighting station signal, leading or lagging by the amount of total correction introduced at the differential. Two separate systems are used, one for azimuth correction, the other for elevation correction. Only the azimuth channel is described in detail, as the two are identical in general design features. Reference to the schematic circuit shown in Fig. 19 will aid in understanding the lead computation process.

Kinematic lead is computed by rate gyroscopes in the sighting station. Two single-degree-of-freedom units are used. Movement of the sight in tracking brings the gyro case up against contacts on the gyro element having the effect of closing a single-pole-double-throw switch to left or right, causing the azimuth total correction motor to drive in a corresponding direction. The necessary feed-back path to the gyro element is via a pair of erecting coils which apply an electro-magnetic torque on the gyro element in such a direction as to precess it away from the contact on the case. A solution has been reached when the motion of the case towards the gyro element is exactly offset by the precession of the element away from the case. Under these conditions, the contacts remain open and the total correction motor is stopped, the correct computation for the problem having been made and the total correction driven into the differential generator.

Summation of all items involved in the total correction is made at the potentiometer resolver unit. This unit is positioned mechanically by gun position and parallax correction. The electrical voltage applied to the potentiometer elements is varied through a network which receives altitude and airspeed, range, and ballistic (chiefly time of flight). The overall d.c. voltage of 28 volts available for the equipment is reduced to 22.5 volts by a precision voltage regulator and this voltage is further modified by the fore-mentioned network before it is applied to the resistance arms of the potentiometer resolver. Precession of the gyro element is controlled by the current through the erecting coils which, in turn, is controlled by the position of the sliding contacts on the potentiometer resolver resistance arms.

The inter-relation of the various items of the computation system is evident from the past discussion. No computation has actually occurred in the computer until the total-correction motors operate and these, in turn, do not operate until the sight station is energized and tracking on the target begins.

The original plan of investigation into the performance of this computing system called for detailed experimental and theoretical analysis of the lead computing gyroscopes, with regard particularly to their sensitivity and frequency response. Unfortunately, no sighting station could be obtained in time to be of use in the present project.

Much time was spent in an effort to synthesize an input circuit resembling that of the sight gyro elements. The contactor type of input can readily be devised but the necessary feedback channel defies all efforts at synthesis. This difficulty arises because of the manner in which all corrections except that due to kinematic lead are applied to change the sensitivity of the lead channel, rather than having all corrections arrive independently at a summation unit for generation of total correction. Consequently, a computed kinematic lead corresponding to a given problem cannot be entered synthetically into the computer for analysis, since the sensitivity of the lead channel is a variable depending on all other factors of the problem. The final conclusion of this part of the study is, therefore, that in any further analysis of this fire control system, the computer and sighting station must be treated simultaneously rather than as independent units.

Such investigation into the lead channel as is possible becomes limited by necessity to a simple study of its response speed. The total correction motors are essentially constant speed. By circuit design they are set to operate at a slow speed during the first 1.5 seconds rotation in response to a given signal from the sight gyros, and then shift to a higher speed if error persists longer than 1.5 seconds in time. The time delay circuit is so constructed that the 1.5 second delay time is measured from each instant of contact closing. This means that when error is small and contacts are closing alternately right and left with a period less than 1.5 seconds, the total correction motors remain at slow speed. High speed is available only when the error signal persists in the same direction for more than the delay time. The chief function of slow speed operation is to improve the smoothing of problem solution and reduce the effect of normal tracking line discrepancies on the average computed lead.

This type of circuit design suffers from a fundamental limitation. Errors, no matter how large, are corrected at slow speed for 1.5 seconds before the total correction motor shifts to high speed. Furthermore, if the computing time required is in the vicinity of 1.5 + to 2.0 seconds, the motor will shift to high speed just as the problem nears solution, resulting in overshooting and lack of smoothness. For greater computing time the problem solution is always approached at high speed, overshot, and then back-corrected at low speed, since the time delay circuit functions as soon as the contact points operate.

Overall speed sensitivity of the lead channels are easily measured in mils of total correction per second. Both slow and high speed sensitivity were determined experimentally for each channel and exact delay time was also measured. This data is presented in Table II.

In Figs. 20 and 21, curves are drawn to show computer solution time required to drive a given total correction value to the selsyn differential and thus to the guns. These curves are plotted on the assumption of no overshoot in the problem solution and an instantaneous shift of speed at the motor upon the expiration of delay time. While somewhat ideal, the results indicate the solution time required by the computer for any total correction within its limits.

Since the computer may conceivably be holding a set-up from a previous problem, the total correction motor may have to drive from a lead in one direction down through zero to a lead in the other direction. The curves of Figs. 20 and 21 are, therefore, drawn to include a maximum total correction change of twice 250 mils, which is the limit in either direction of the azimuth or elevation channel.

The study of the total correction channels which are fundamentally lead-computing channels modified in sensitivity to include all fire-control corrections, indicates that the computer solution time is a variable controlled by the type of problem to be solved. This variable relationship is essentially discontinuous and made up of two linear functions of total correction versus time as shown in Figs. 20 and 21. Generally, solution time increases with the amount of lead required by the problem.

The characteristics of the lead computing system may be briefly summarized as follows:

1) Solution time increases with total correction required, whence it follows that the computer takes longest time to reach a correct solution to a high speed problem.

2) Problems are slowed unduly in their solution because the total correction system operates at slow speed for the first 1.5 seconds of solution time.

3) The overall action of the computer discriminates against the high speed problem where lead and solution time are greatest, but where the greatest rapidity of solution is needed, since firing time in these problems is at a minimum.

4) The manner in which kinematic lead is introduced to the computer prevents adequate synthesis of problems unless a sighting station is available to use in conjunction with the computer itself.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Each main section of the computer has been analyzed experimentally and theoretically to the limit of available equipment and treated in a separate chapter. In this last chapter all results are coordinated to present a complete picture of computer performance, final conclusions are drawn, and recommendations made for further study.

Recapitulation of results is made in an orderly form below:

1) The Range Input Unit approximates a proportional servomechanism, with a natural frequency of 1.187 cycles per second and a damping ratio of 0.445. The maximum value of the resonance function, θ_o/θ_i, is 1.20. (Reference, Figs. 5, 6, and 10.)

2) Errors in present range produced by the velocity of range input, i.e., range rate, are a maximum of about 40 yards at 700 miles per hour and decrease approximately at a linear rate for lower range rates. (Reference, Figs. 7 and 10.)

3) The minimum error existing in the range channel as determined by the amplifier and follow-up motor sensitivity is a variable, averaging about 2.5 yards at minimum range and increasing to 19.0 yards at maximum range. (Reference, Figs. 7 and 10 for intermediate points.)

4) Range input accuracy is limited chiefly by the maximum speed of the follow-up motor which is such that range rates of 700 miles per hour cannot be followed below 1000 yards present range. Furthermore, this defect becomes progressively more serious with decreasing range so that at 500 yards present range the maximum range rate input is only 378 miles per hour. (Reference, Table IV for complete tabulation.)

5) The Azimuth and Elevation Input Channels approximate proportional servomechanisms with a natural frequency of 2.1 in the azimuth channel and 1.69 in elevation. Values of the damping ratio were in the range of good engineering practice, 0.51 for azimuth, 0.47 for elevation. The difference in natural frequency is due to the different equivalent mass of units driven by the two input channels. Fundamentally they are identical. (Reference Figs. 12, 13, 14, and 15.)

6) The steady state errors in the azimuth and elevation channels resulting from input velocities in these quantities are appreciable and appear in the lead computing system. This is largely a result of using only a one-speed synchro feedback system in the computer. The turret servo-amplifiers give better response since both one-speed and 31-speed synchros are used. The positional error introduced into the lead computing system results in a small error in the computed lead. This error as finally received by the guns is within their dispersion pattern. (Reference Figs. 17 and 18.)

7) The Altitude and Airspeed Input Channel is controlled by a potentiometer servomechanism very similar to the Range Unit. Its response characteristics are very poor. However, on the assumption that altitude and airspeed changes will be negligible during a firing run, its response to oscillations and its velocity steady-state error are of little interest. No Handset Unit was available to conduct experimental tests.

8) The total correction channel operates as an unusual type of servomechanism, having variable, non-linear sensitivity, so designed as to combine kinematic lead correction which is directly generated in this channel, with the other corrections of the fire control problem generated mechanically elsewhere in the computer.

9) Response of the total correction channel is relatively slow. Problem solution is further slowed by the method of smoothing used, consisting of driving the channel mechanism at about ½ speed and for 1½ seconds delay time before shifting to high speed.

10) Solution time of the system is chiefly a function of the total correction channel, increasing in a general linear fashion as the amount of lead correction required in a given problem increases. Curves of solution time versus total correction required are drawn. (Reference Figs. 20 and 21.) It must be noted, however, that solution time is not a simple function of the problem being solved since the computer is not self-zeroing but starts towards the new solution from the values remaining set in from the previous problem.

11) The computer unit, considered in its entirely, discriminates against the high velocity problem in both the range and total correction channels. Consequently, solution time and errors in solution are greatest when rapid solution and good accuracy are most needed.

12) The overall design of the computer unit is such as to prevent adequate introduction of synthetic problems for laboratory tests unless used in conjunction with the sighting station.

The computation system of the Central Station Fire Control System was found generally adequate in principle and static sensitivity. The weak features of the design are chiefly caused by poor dynamic response in the servomechanism channels. Suggested recommendations for improving this response are:

1) Raising of the natural frequency of all servomechanisms used in the computer by a factor of at least 3 and preferably more.

recent circuit developments permit ready accomplishment of this by use of suitable electric networks.

2) Substitution of continuous type servomechanisms for the relay contactor type installed. Phase controlled, two-phase 400 cycle systems should be the ideal solution.

3) Improvement in the maximum driving speed of all input channels, particularly the range and total correction units.

Further study into the performance of the Central Station Fire Control System remains to be undertaken. The following lines of attack are suggested:

1) Overall response characteristics of the total correction channel, with particular reference to smoothing of tracking discrepancies, can be obtained through use of a sighting station in conjunction with the computer, oscillating the sight head at various frequencies to make a transfer locus study.

2) The lead gyroscope sensitivities can be determined by rotating the sighting station at known angular velocities and measuring the erection coil currents required to open the total correction motor contacts.

3) Overall sensitivity of the computer-sight combination can be determined by introducing simple problems to the system and observing the values of total correction generated. Accuracy of this sensitivity can be checked against theoretical computations based on the same sample problems.

APPENDIX

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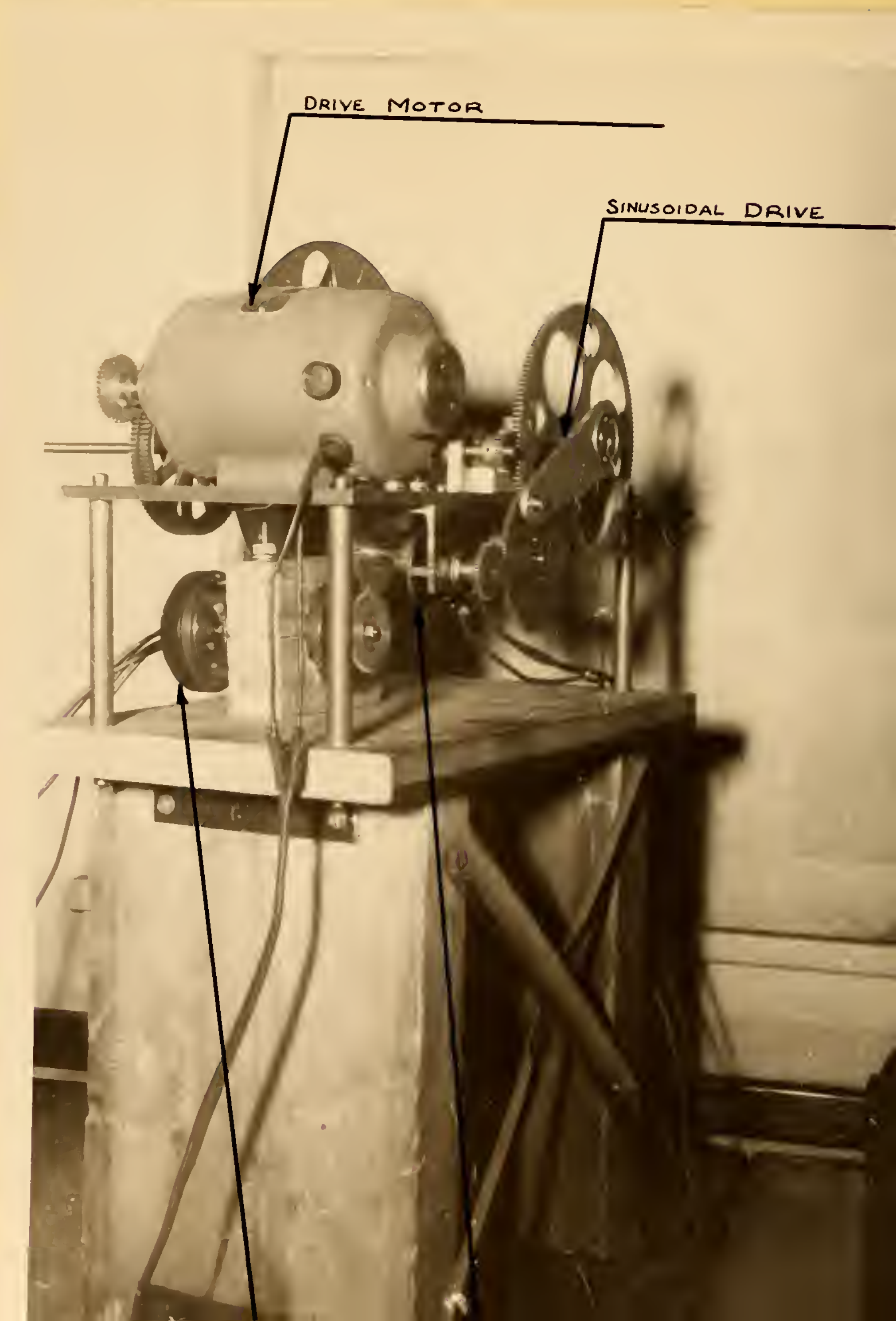


PLATE I

MECHANICAL OSCILLATOR

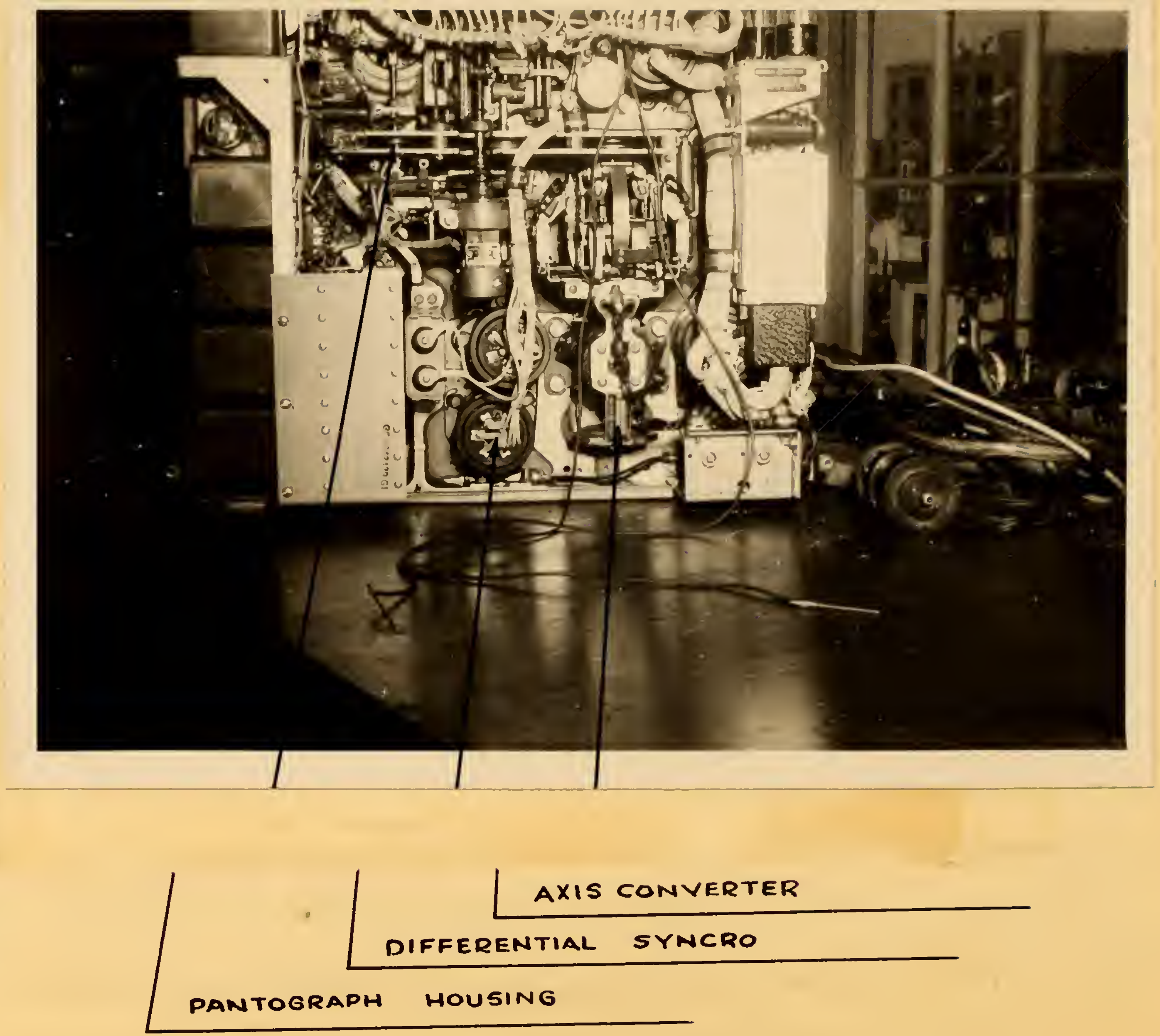


PLATE 2

BACK VIEW OF COMPUTER

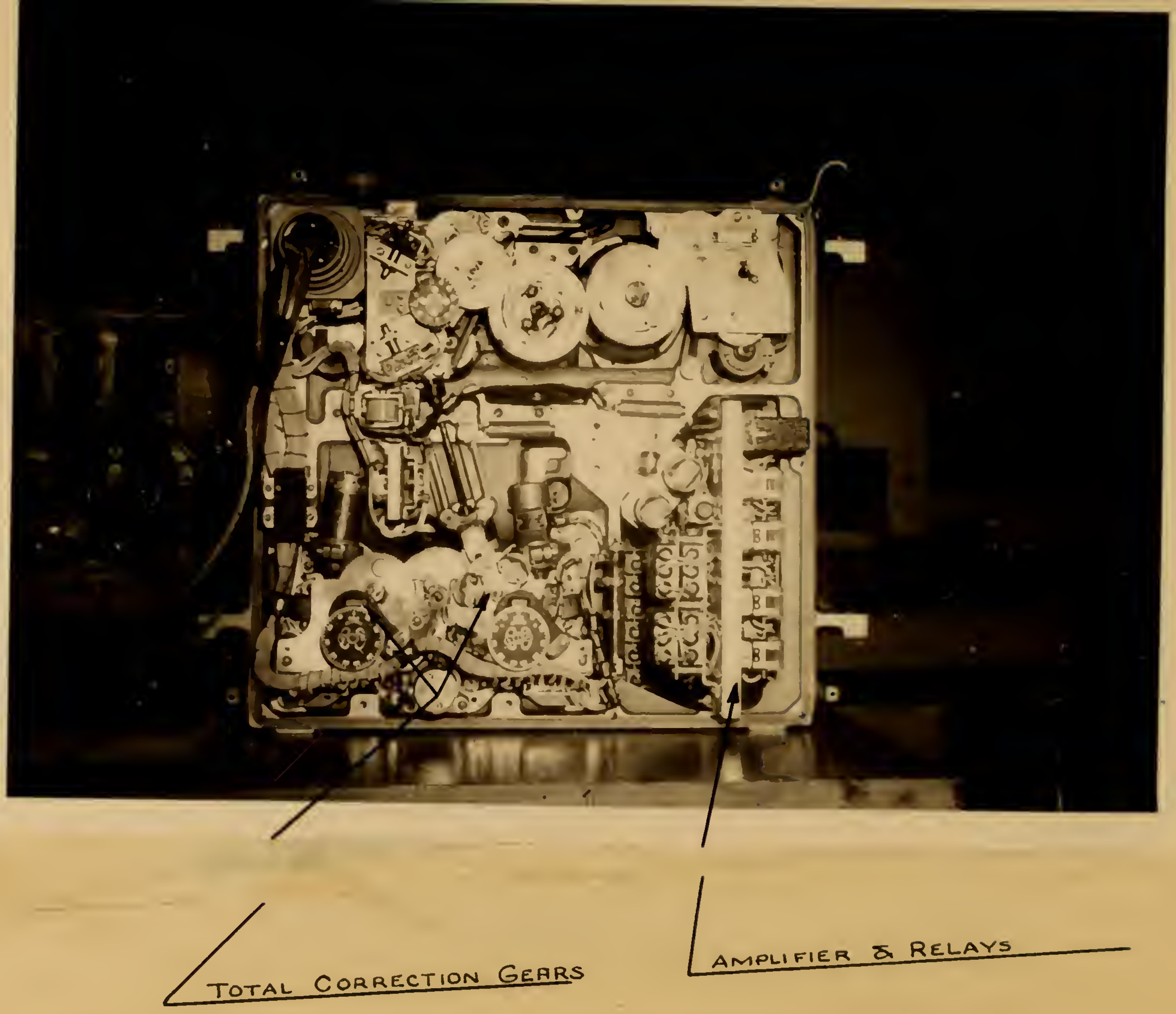


PLATE 3

FRONT VIEW OF COMPUTER

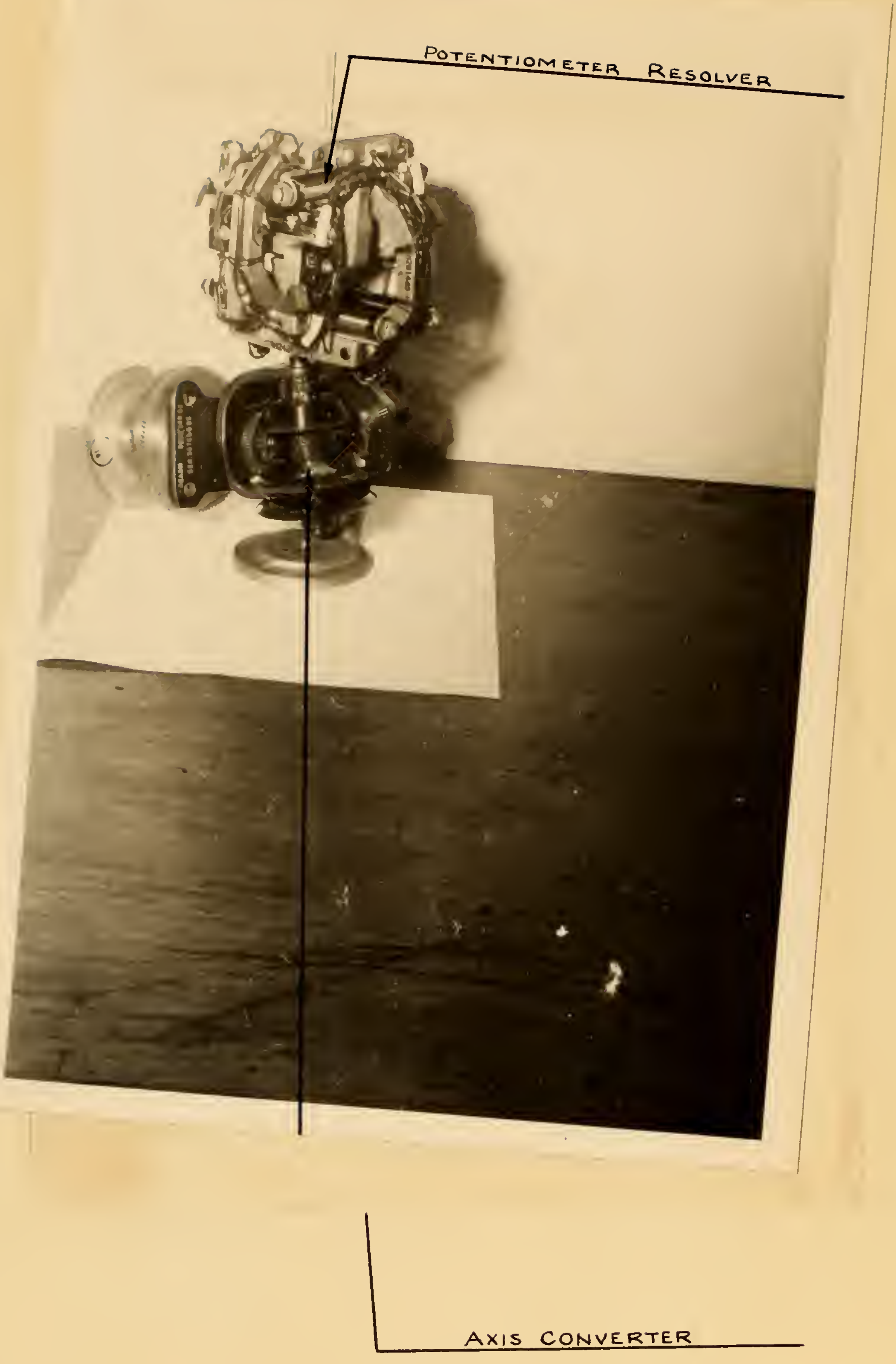


PLATE 4

AXIS CONVERTER & POTENTIOMETER RESOLVER

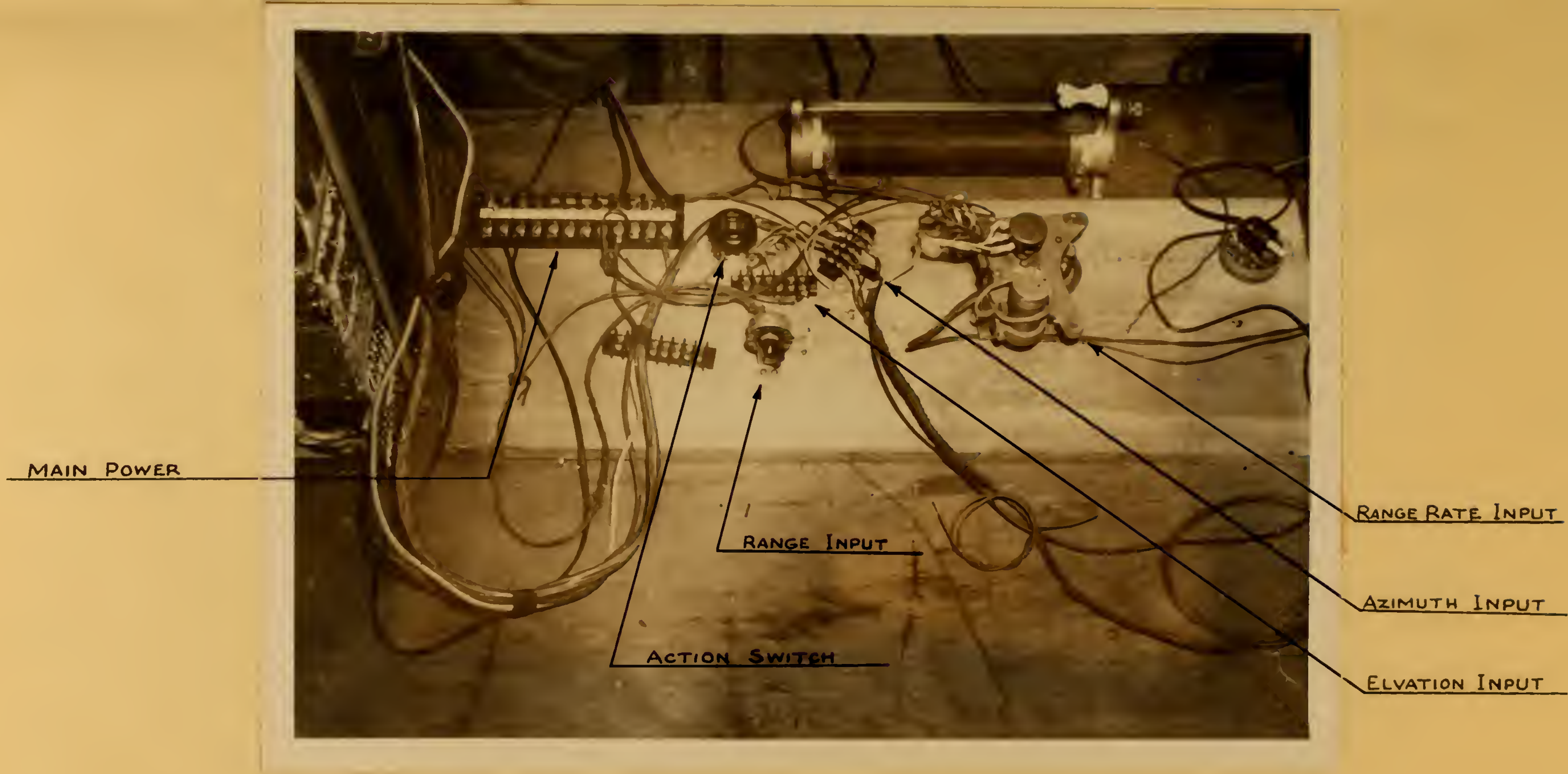


PLATE 5

BREAD BOARD LAYOUT OF INPUT TERMINALS

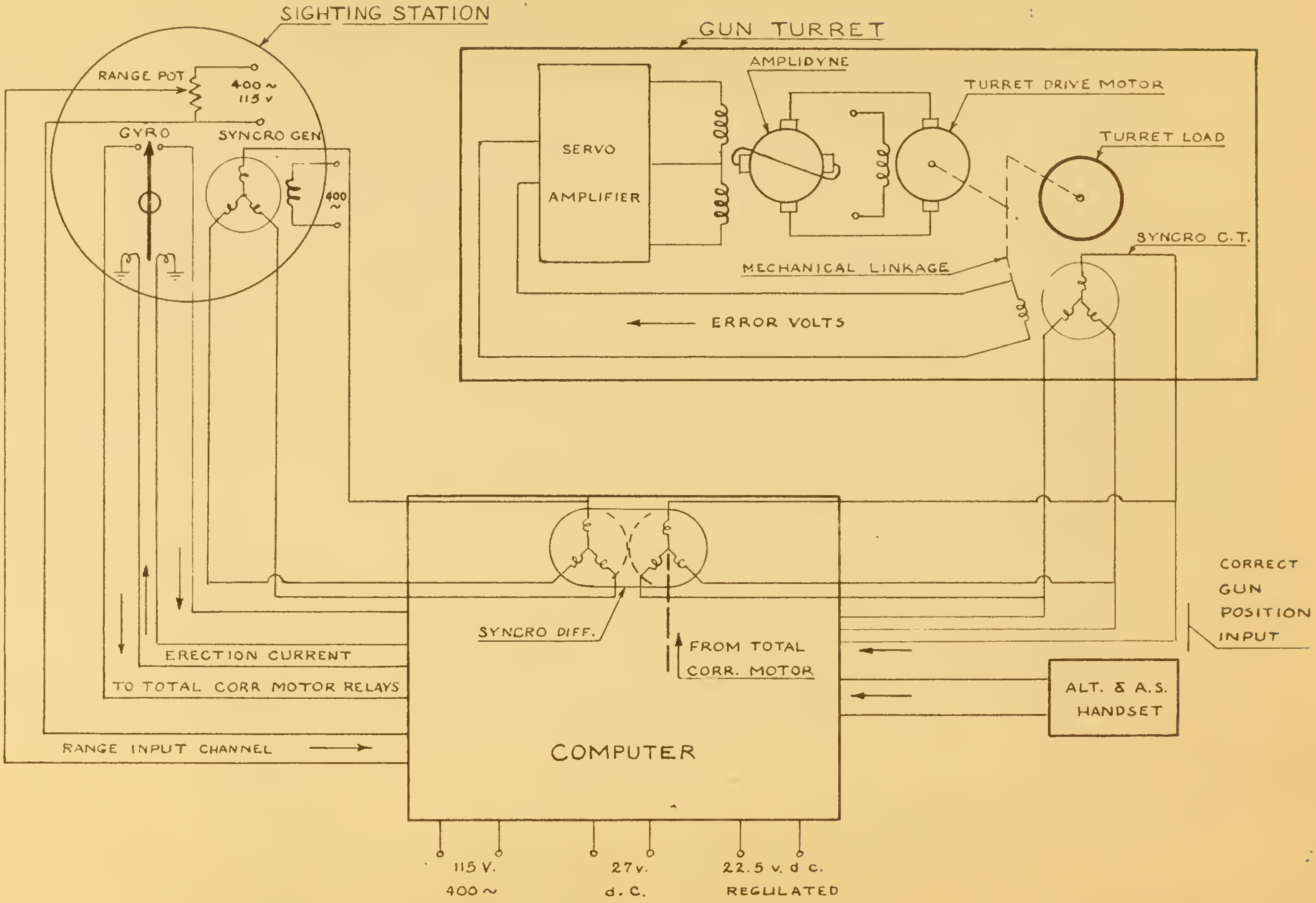


FIG. 1

Schematic Diagram of the Central Fire Control System.

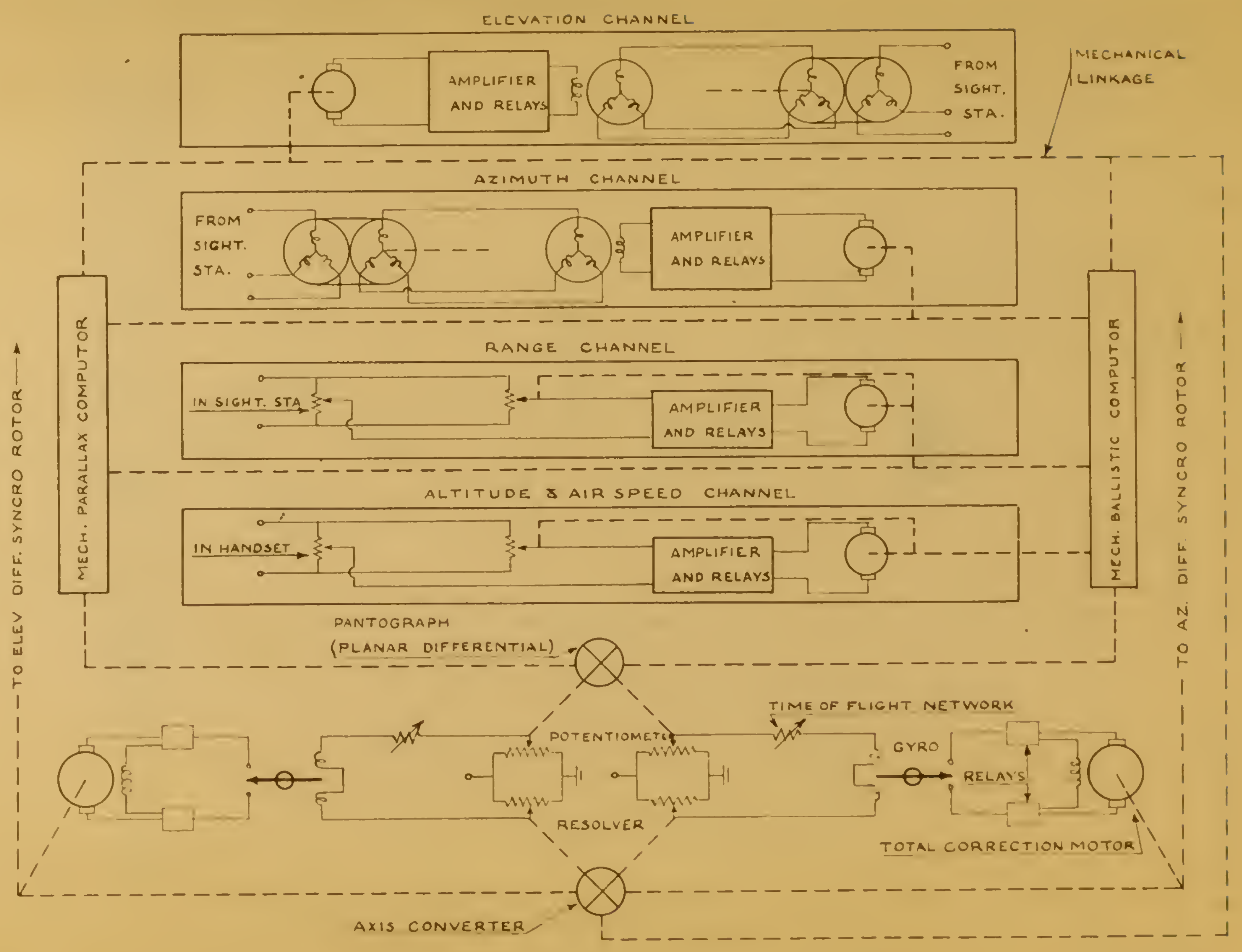
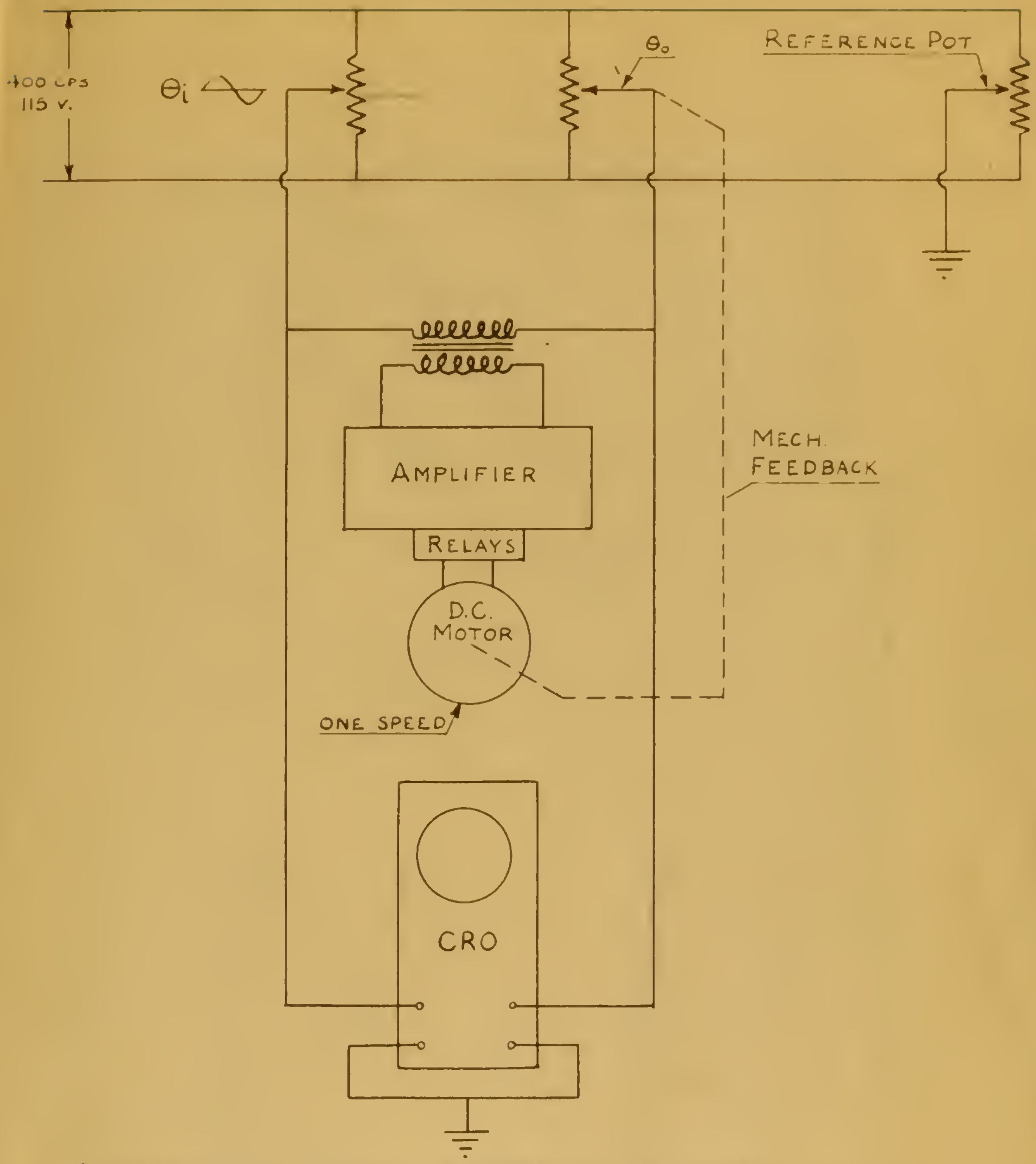


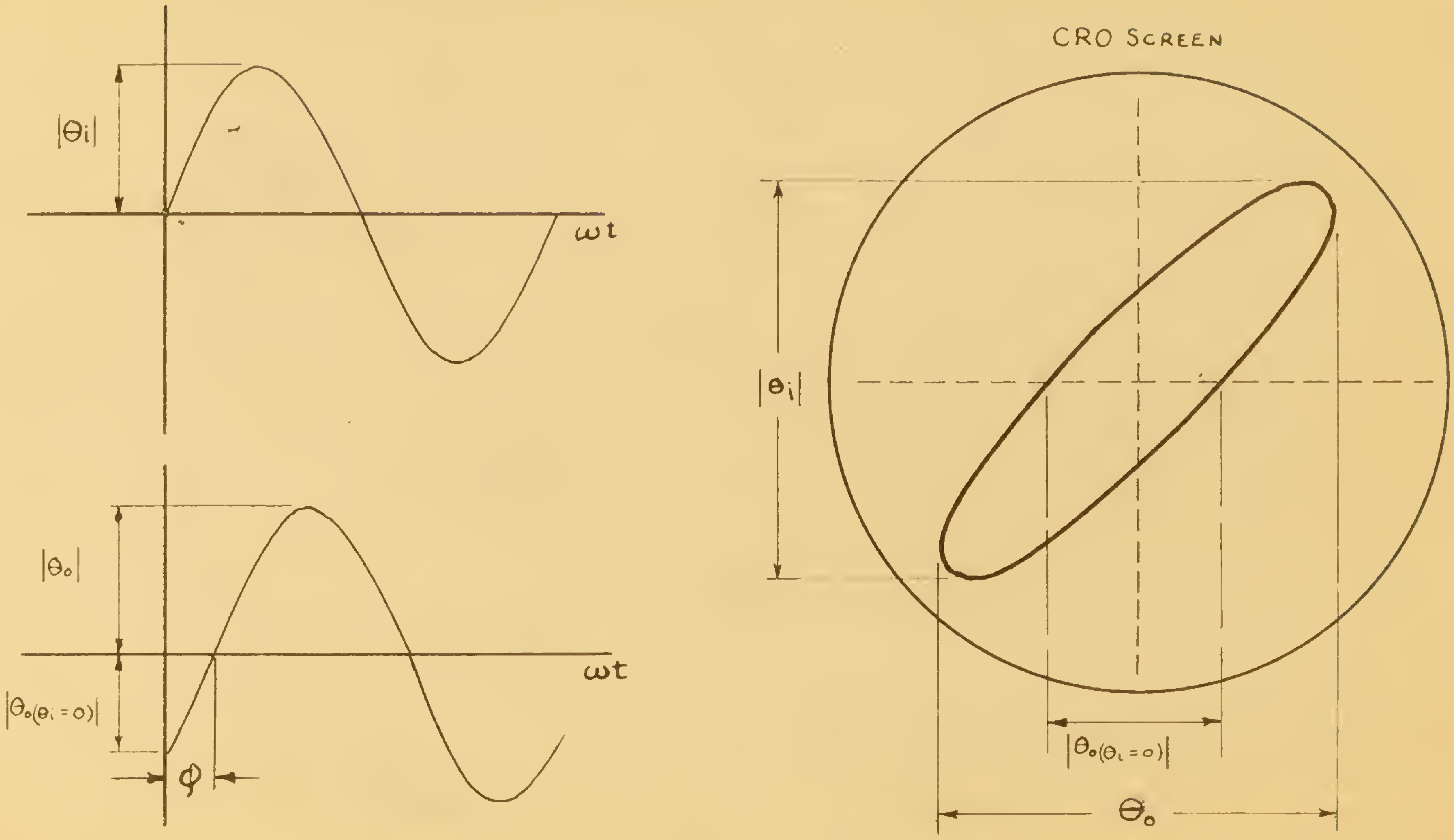
FIG. 2
THE COMPUTER SERVOMECHANISMS



REFERENCE POT IS USED TO ELIMINATE FIXED VOLTAGES —— ONLY VOLTAGE TO CRO IS THAT VARIATION ABOUT THE ZERO AXIS INTRODUCED BY THE θ_i POT.

FIG. 3

POTENTIOMER RANGE SERVOMECHANISM
AND
CATHODE RAY OSCILLOSCOPE FOR FREQUENCY RESPONSE STUDIES
SIMPLIFIED DIAGRAM



PHASE LAG IS DETERMINED BY $\varphi = \sin^{-1}\left|\frac{\theta_o(\theta_i=0)}{\theta_o}\right|$

FIG. 4

CATHODE RAY OSCILLOSCOPE FOR FREQUENCY RESPONSE STUDIES
DETERMINATION OF AMPLITUDE AND PHASE LAG

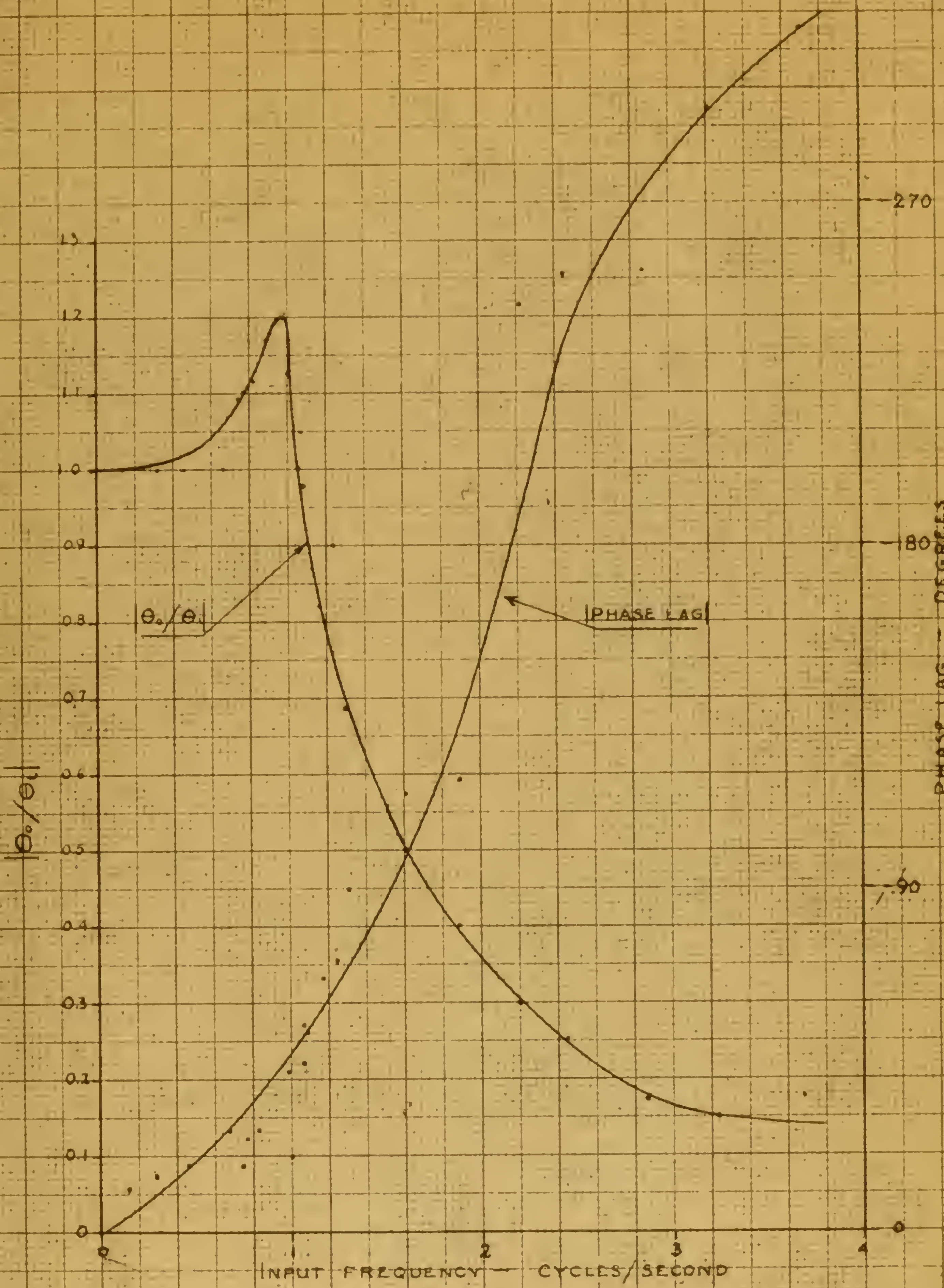


FIG. 5

RANGE OUTPUT RESPONSE CURVES, MAGNITUDE AND PHASE

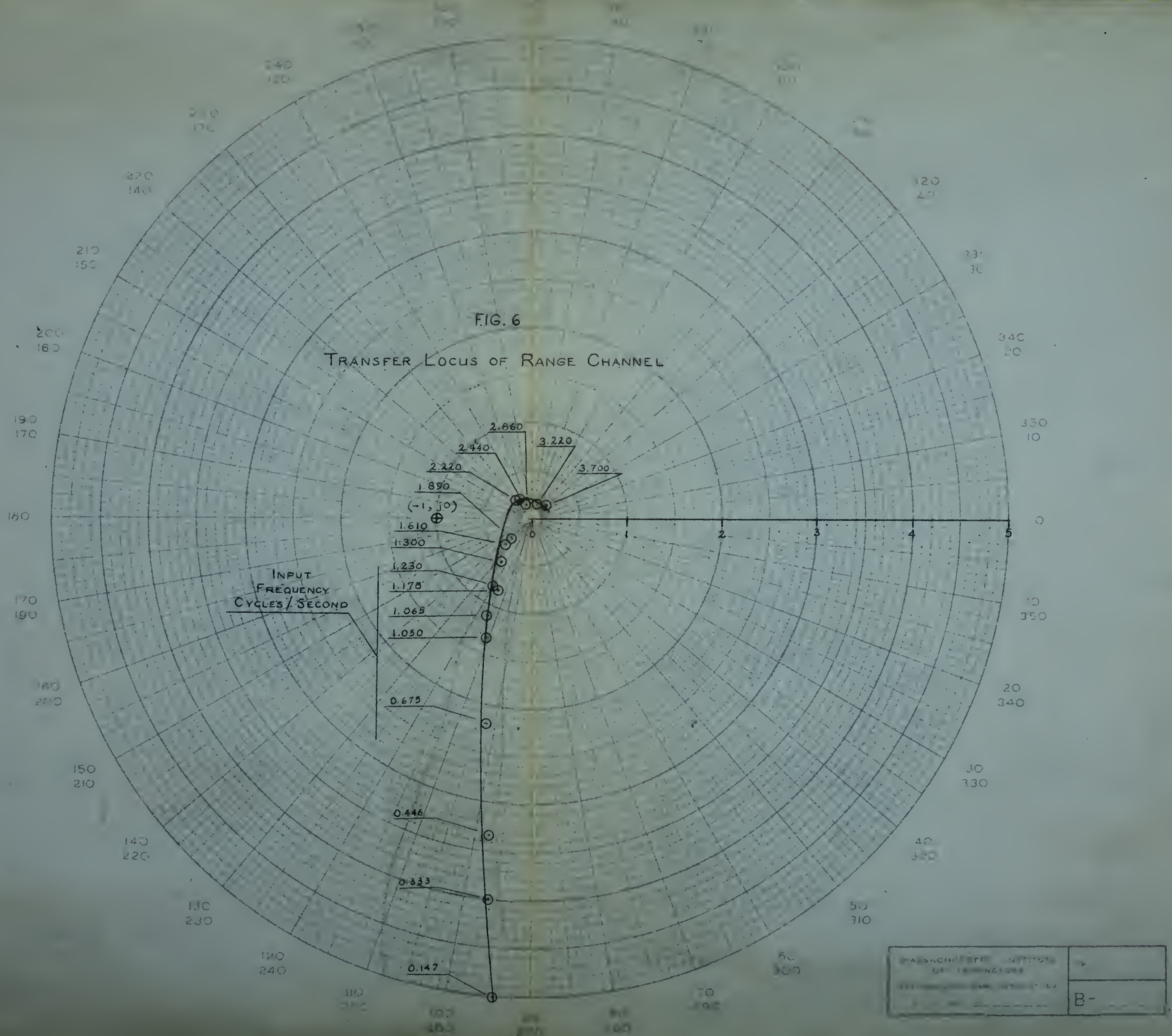


FIG. 6

TRANSFER LOCUS OF RANGE CHANNEL

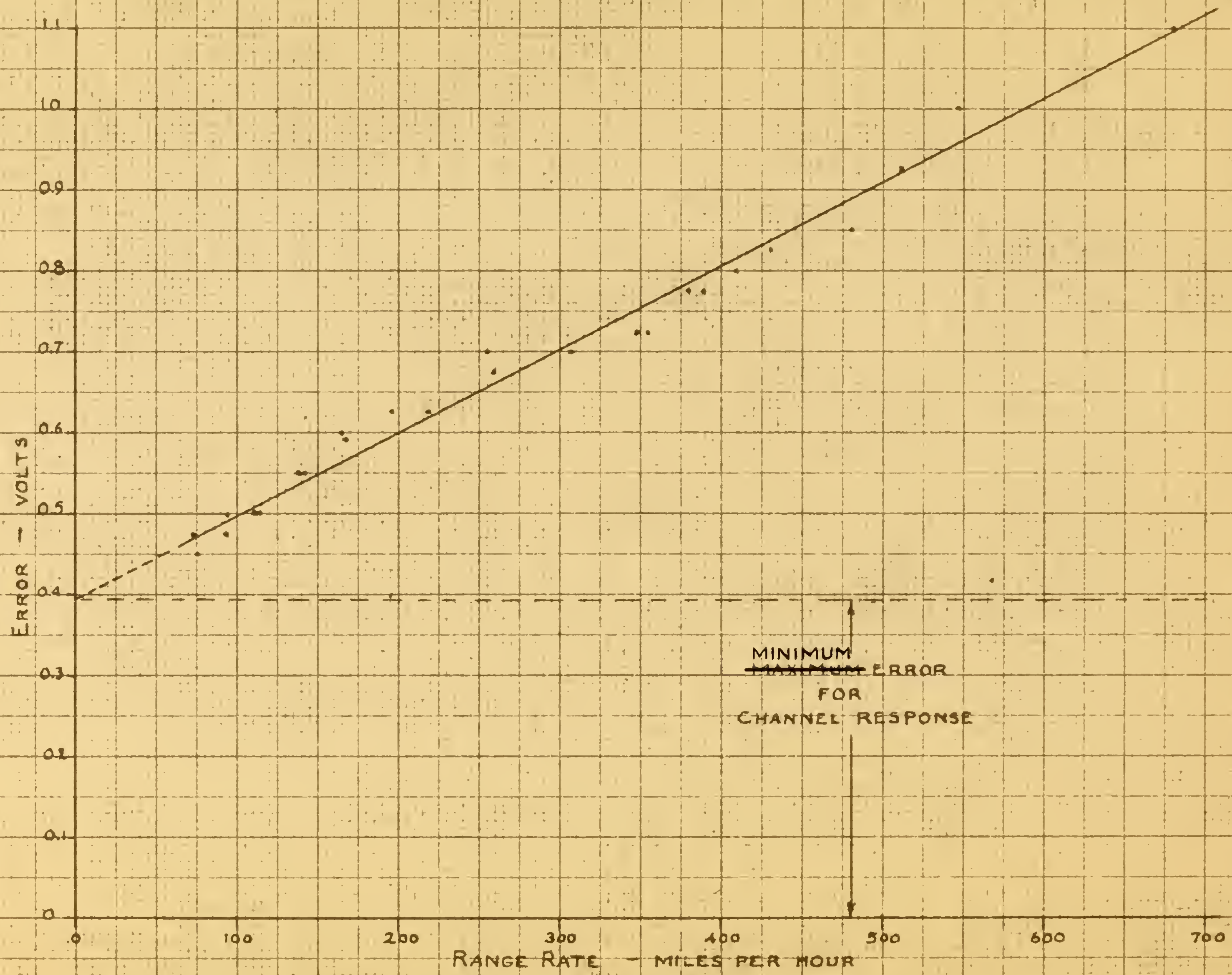
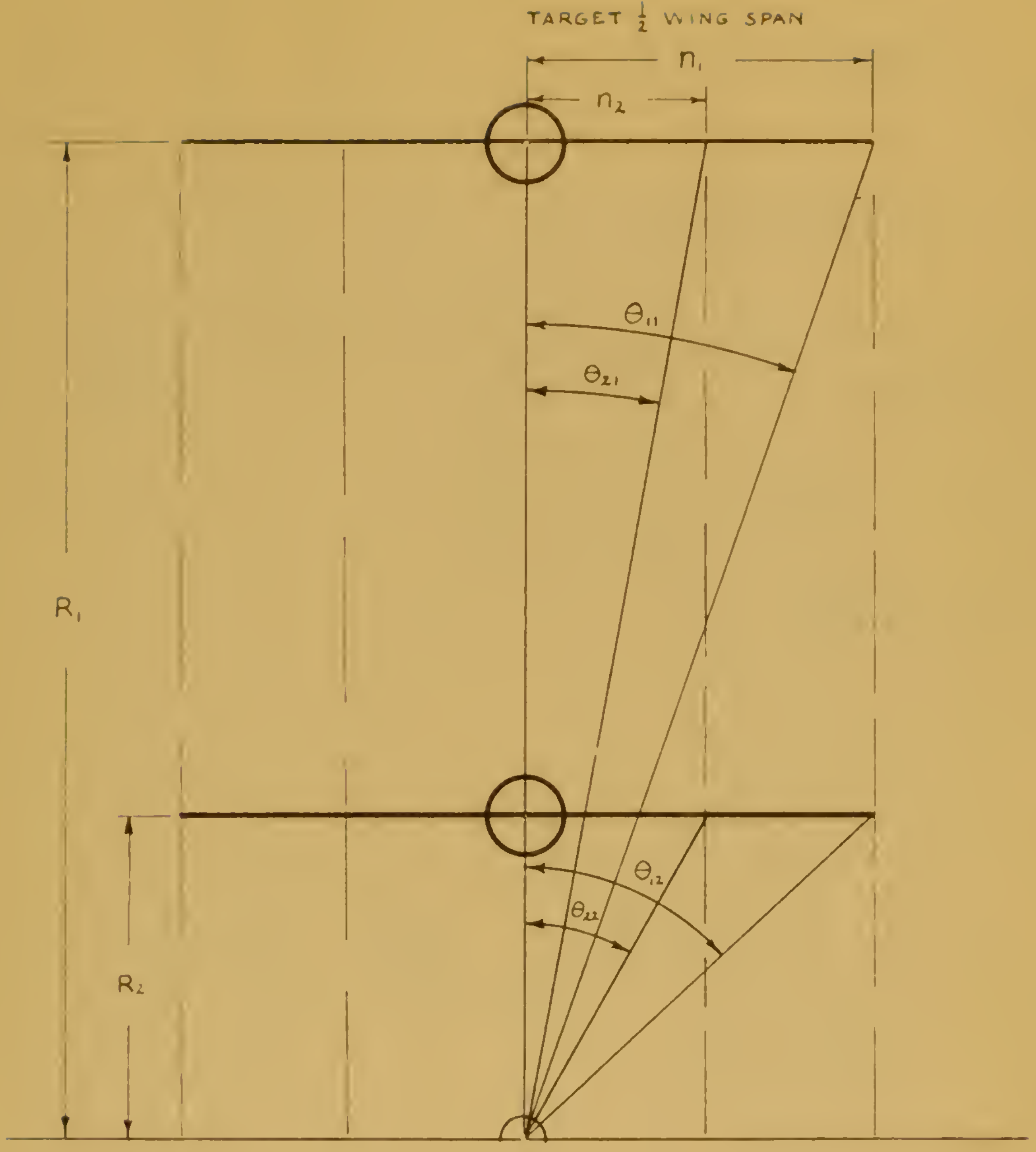


FIG. 7

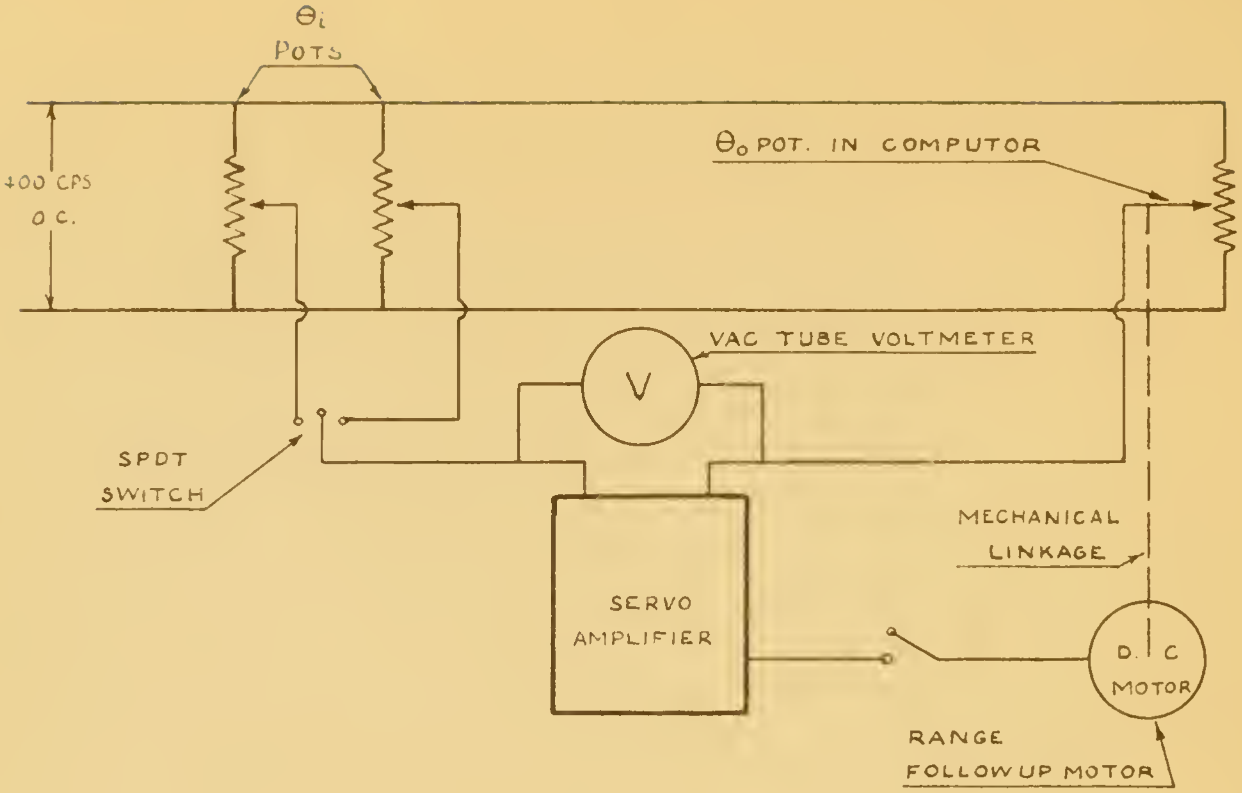
VELOCITY ERROR DUE TO RANGE RATE

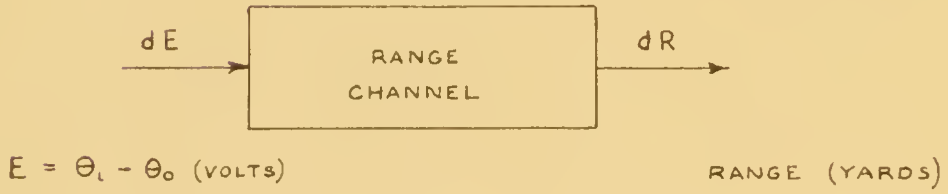


$$\tan\theta = \frac{n}{R} \quad \text{OR} \quad \theta = \tan^{-1}\frac{n}{R}$$

FIG. 8

STADIAMETRIC RANGING





$$S_{ER} = \frac{dR}{dE} \cong \frac{\Delta R}{\Delta E}$$

FIG. 9

Schematic Circuit for Determination of Range Sensitivity

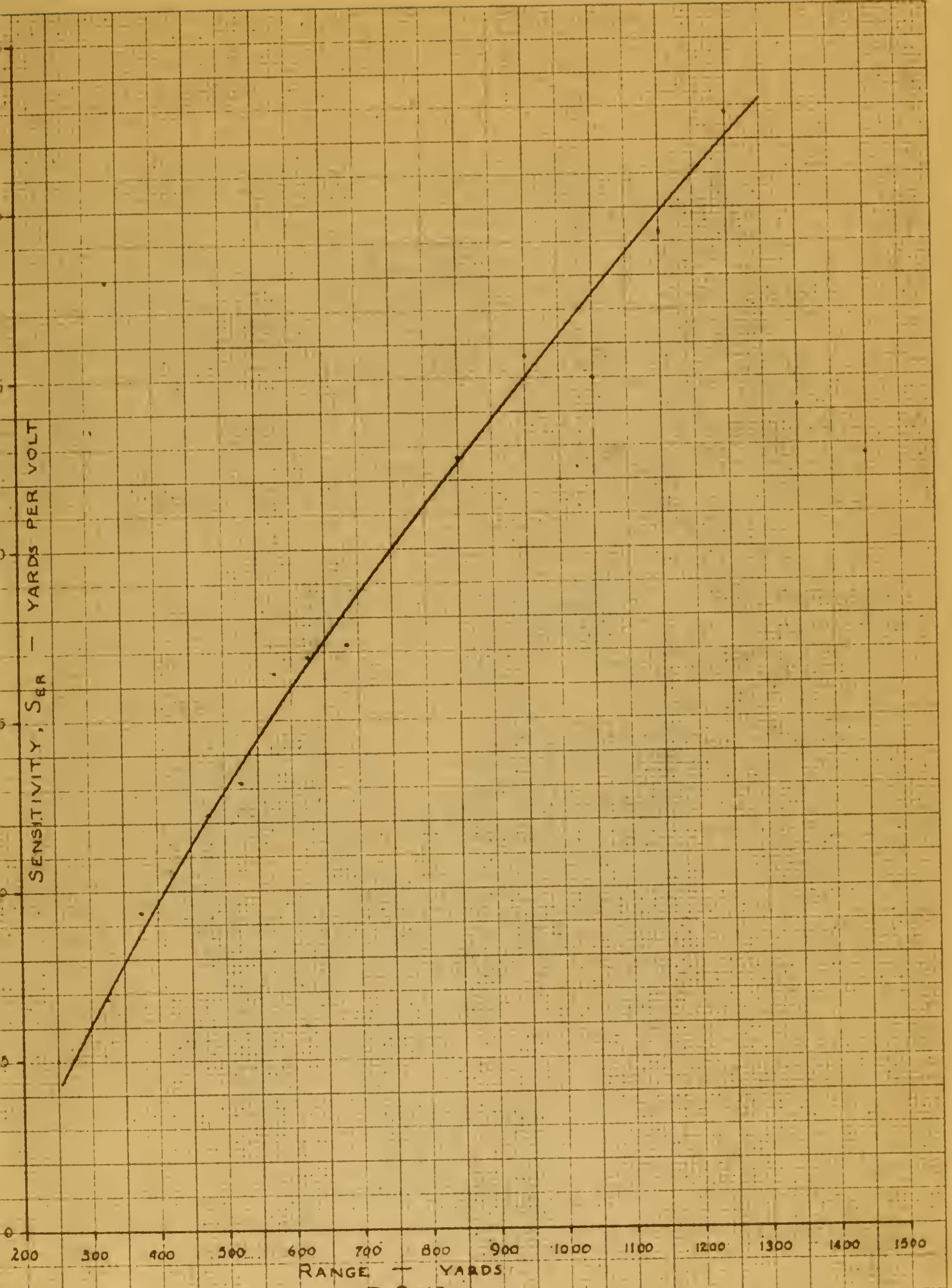


FIG. 10

COMPUTOR RANGE CHANNEL SENSITIVITY VERSUS PRESENT RANGE

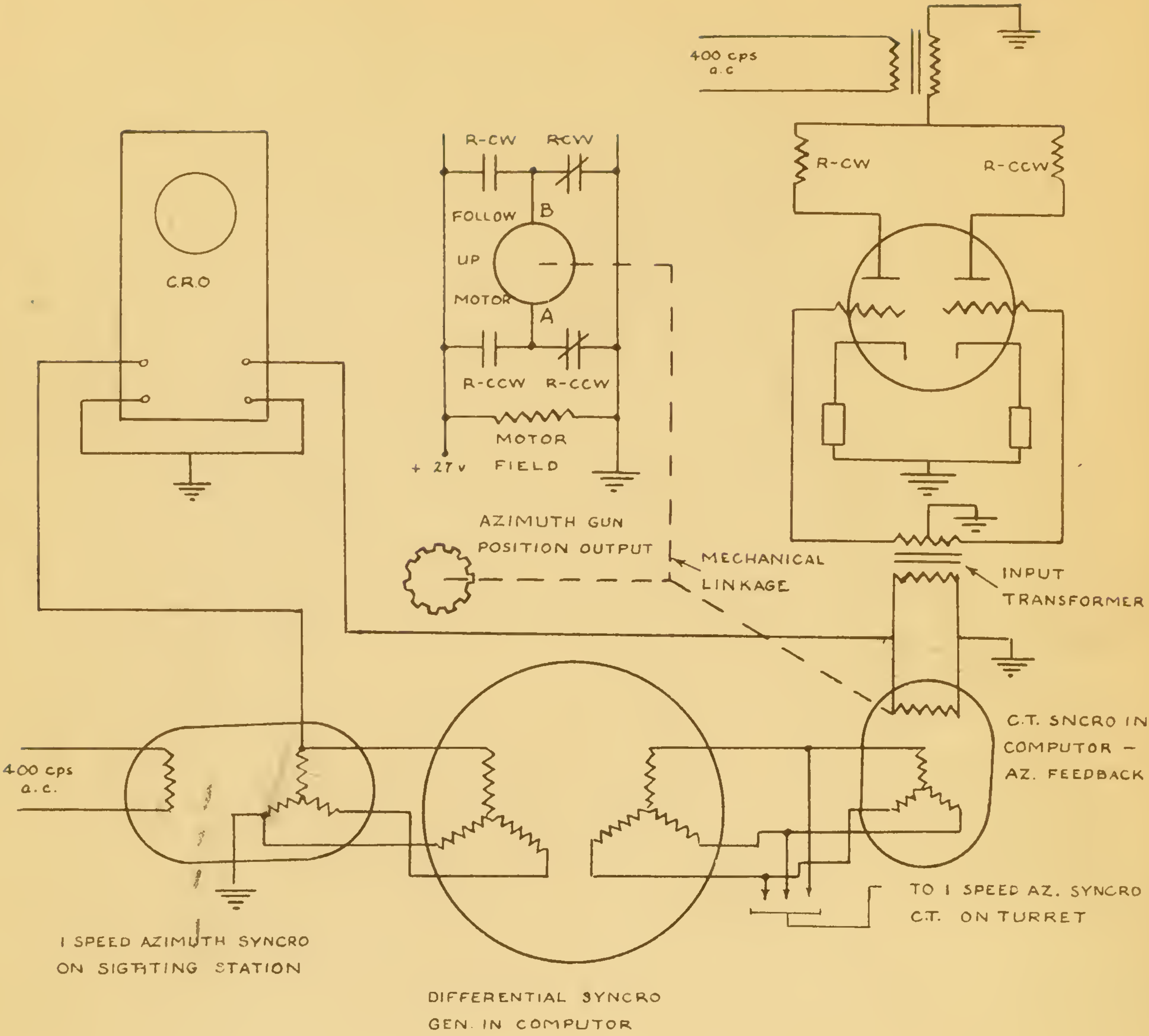
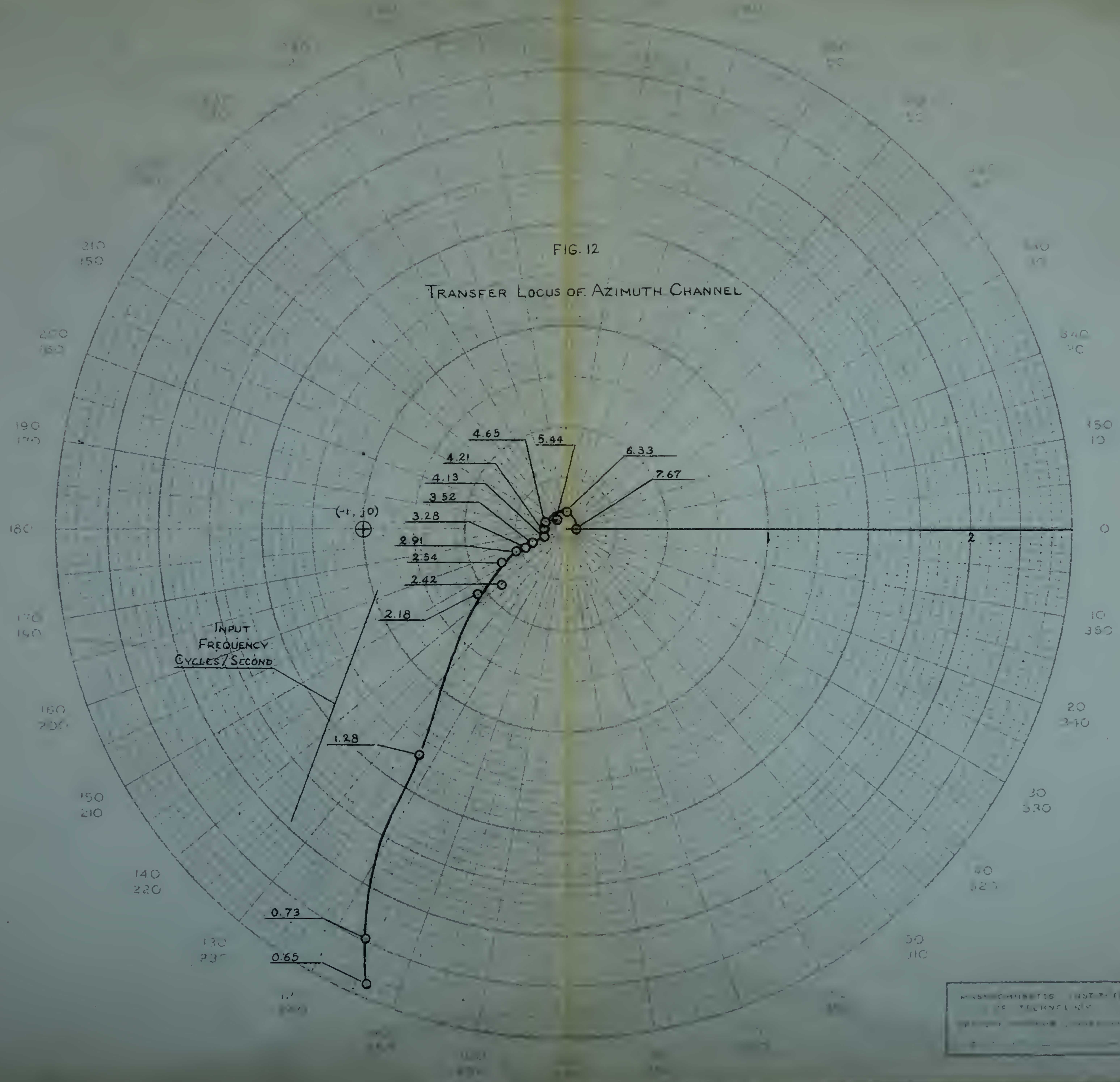

400 cps a.c
R-CW
R-CCW
C.R.O
R-CW
RCW
FOLLOW UP MOTOR
B
A
R-CCW
R-CCW
MOTOR FIELD
+ 27 v
AZIMUTH GUN POSITION OUTPUT
MECHANICAL LINKAGE
INPUT TRANSFORMER
400 cps a.c.
C.T. SNCRO IN COMPUTOR – AZ. FEEDBACK
TO 1 SPEED AZ. SYNCRO C.T. ON TURRET
1 SPEED AZIMUTH SYNCRO ON SIGHTING STATION
DIFFERENTIAL SYNCRO GEN. IN COMPUTOR

FIG. 11

Schematic Diagram Showing Operation of Syncro Azimuth Servomechanism and the use of the Cathode Ray Oscilloscope for Frequency Response Studies.

FIG. 12

TRANSFER LOCUS OF AZIMUTH CHANNEL



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B-

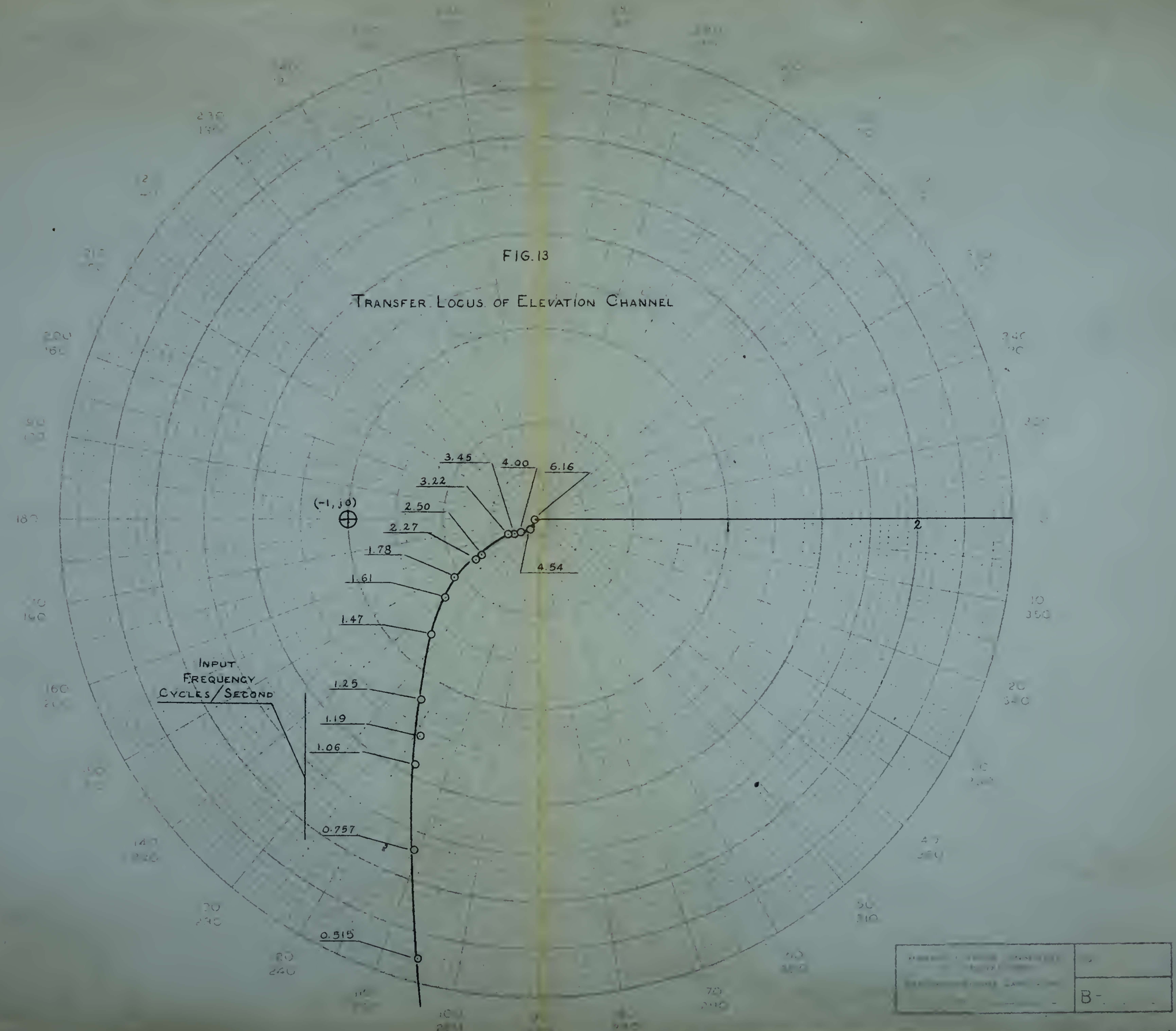

FIG. 13

TRANSFER LOCUS OF ELEVATION CHANNEL

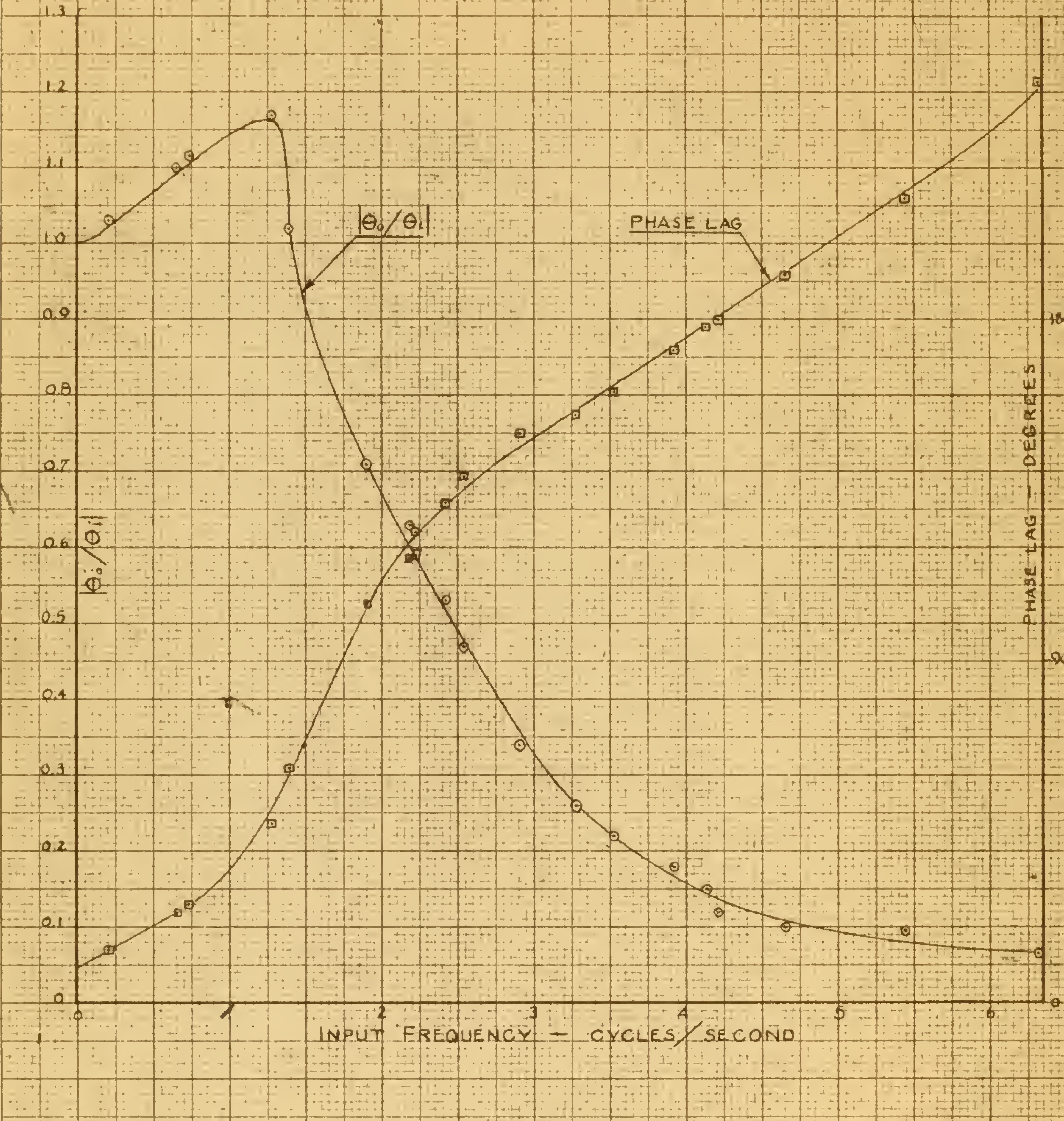

FIG. 14

AZIMUTH OUTPUT RESPONSE CURVES, MAGNITUDE AND PHASE

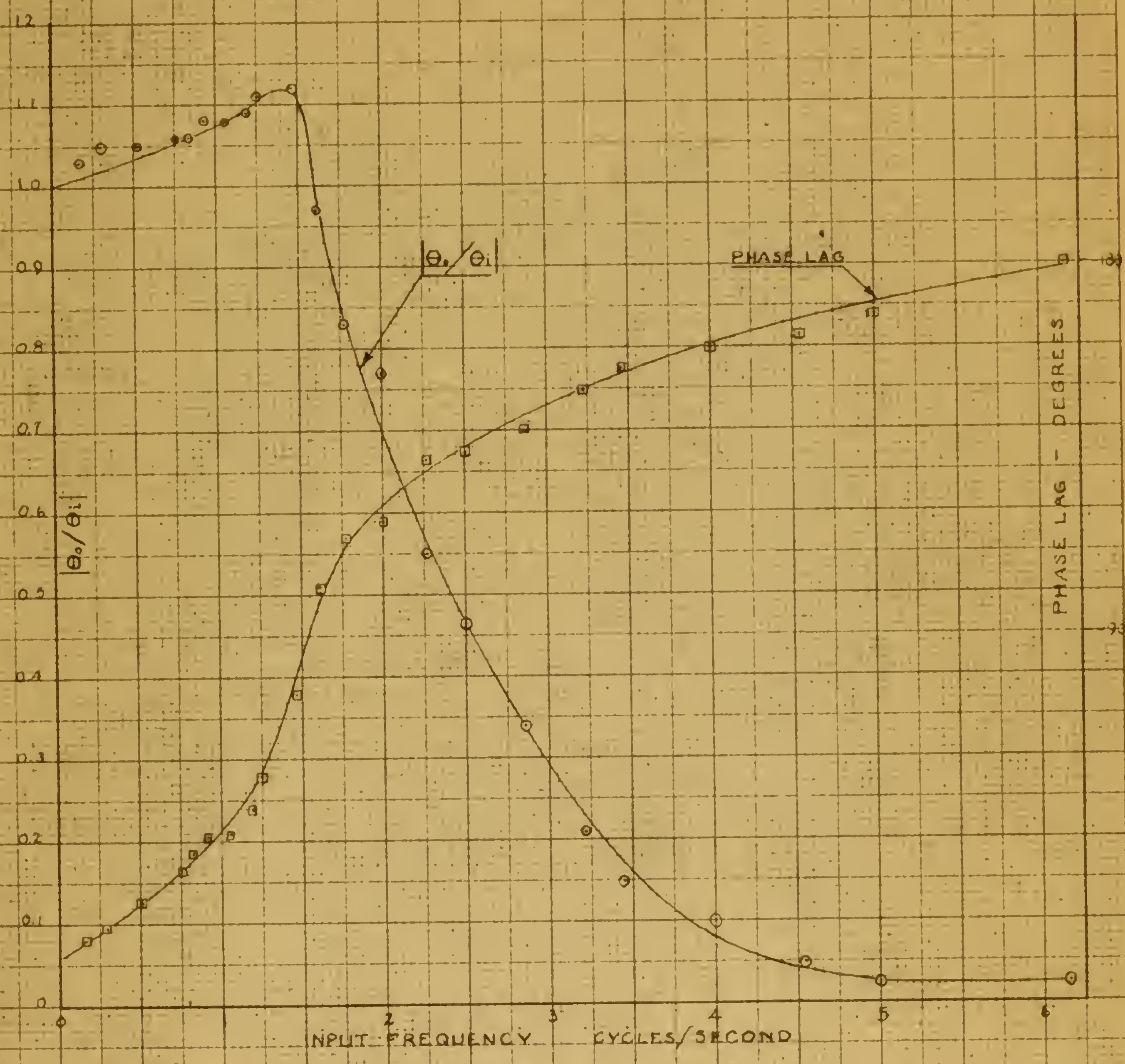

FIG. 15

ELEVATION OUTPUT RESPONSE CURVES, MAGNITUDE AND PHASE

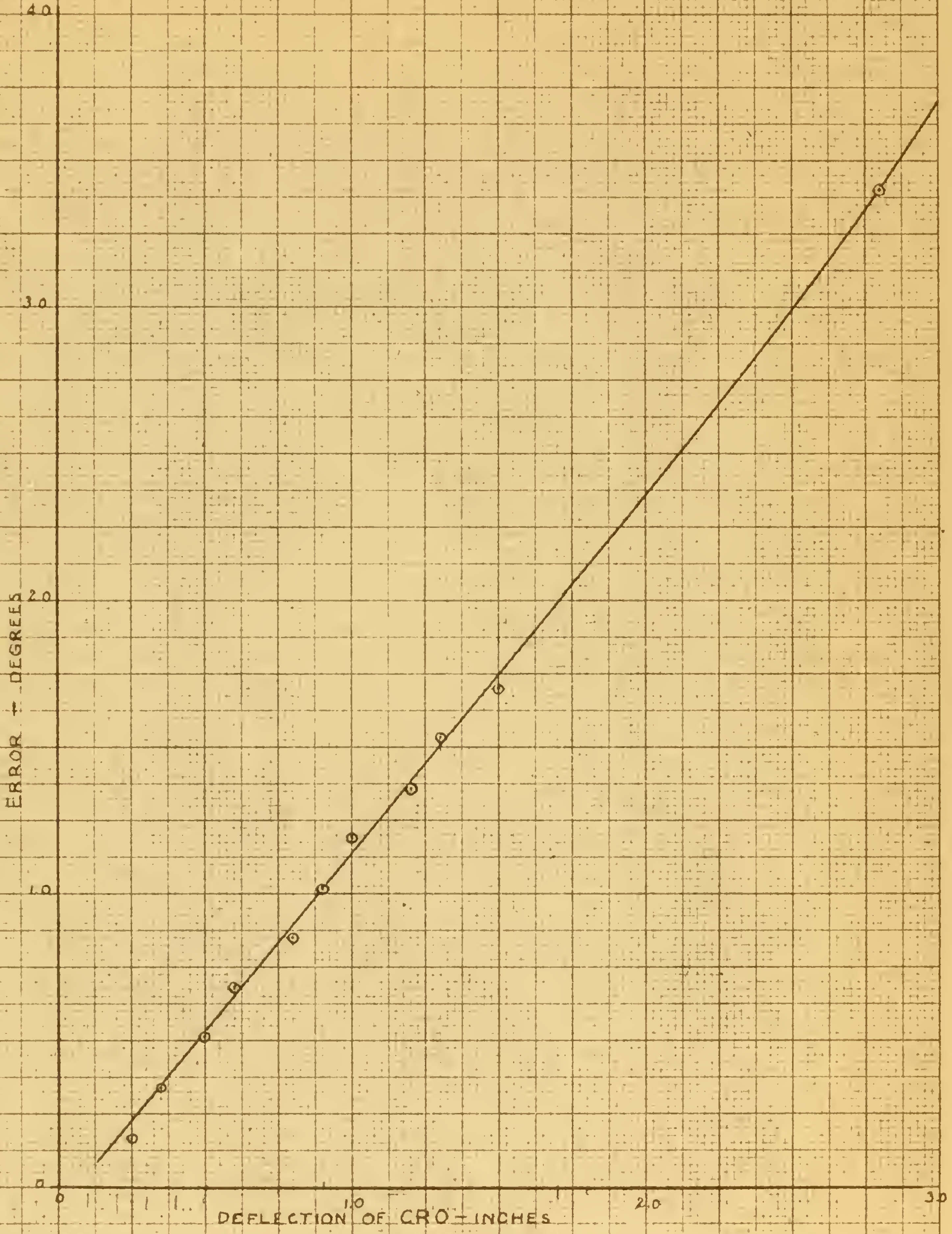

FIG. 16

CALIBRATION CURVE FOR VELOCITY STUDIES

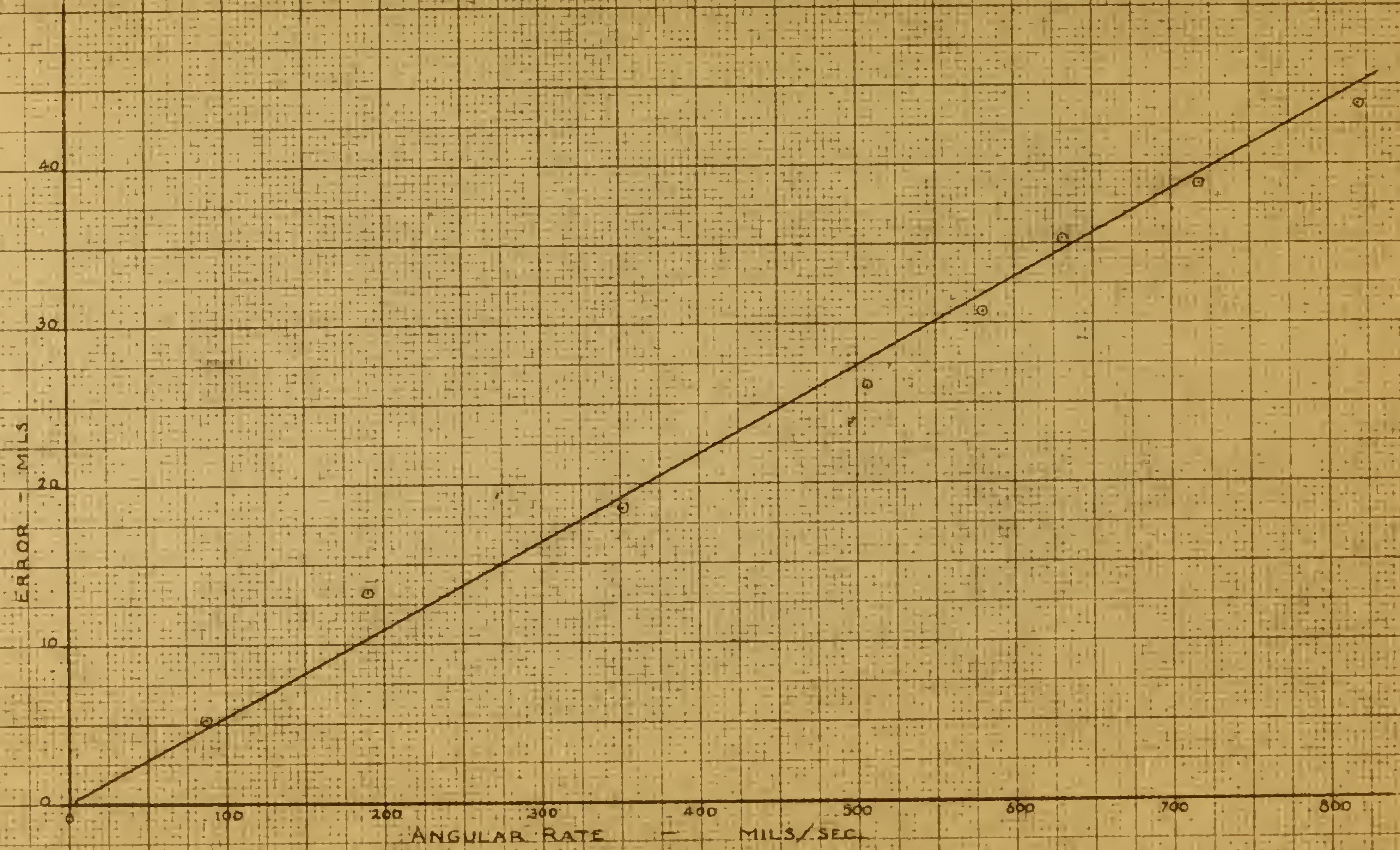

FIG. 17

STEADY STATE ERROR FOR CONSTANT ANGULAR RATES, AZIMUTH

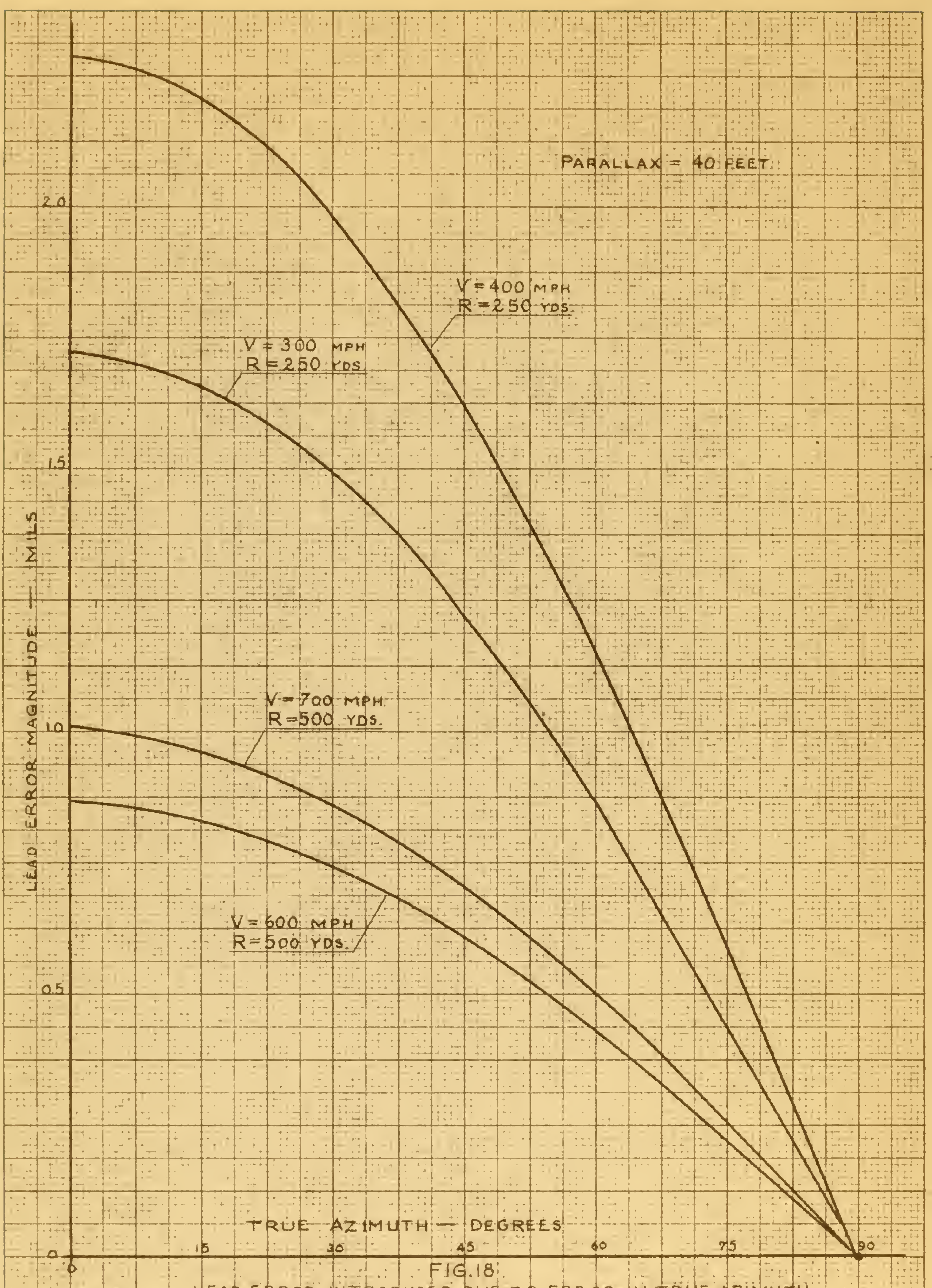

FIG. 18
LEAD ERROR INTRODUCED DUE TO ERROR IN TRUE AZIMUTH SENT TO LEAD COMPUTOR

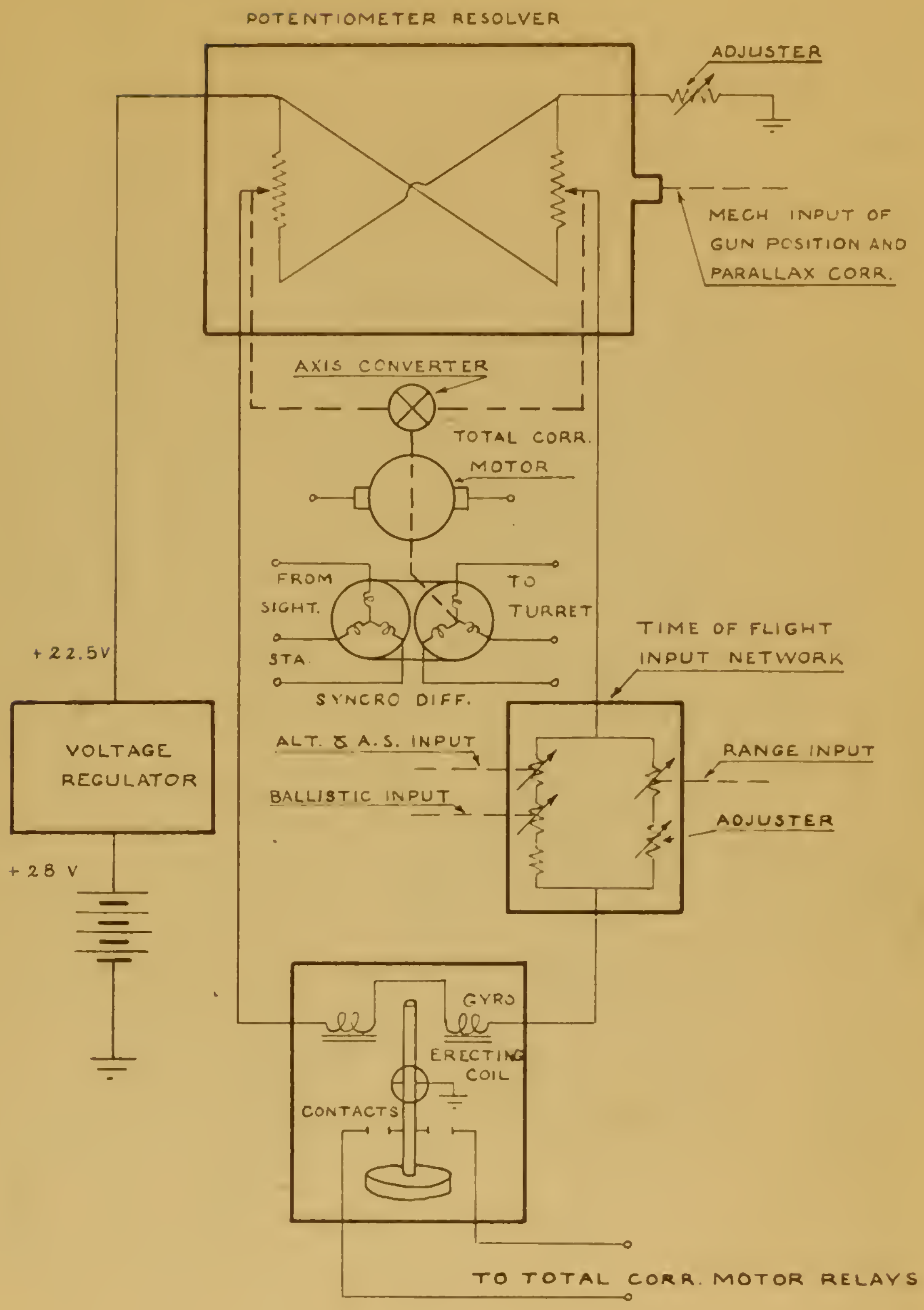

FIG. 19

LEAD COMPUTATION SCHEMATIC

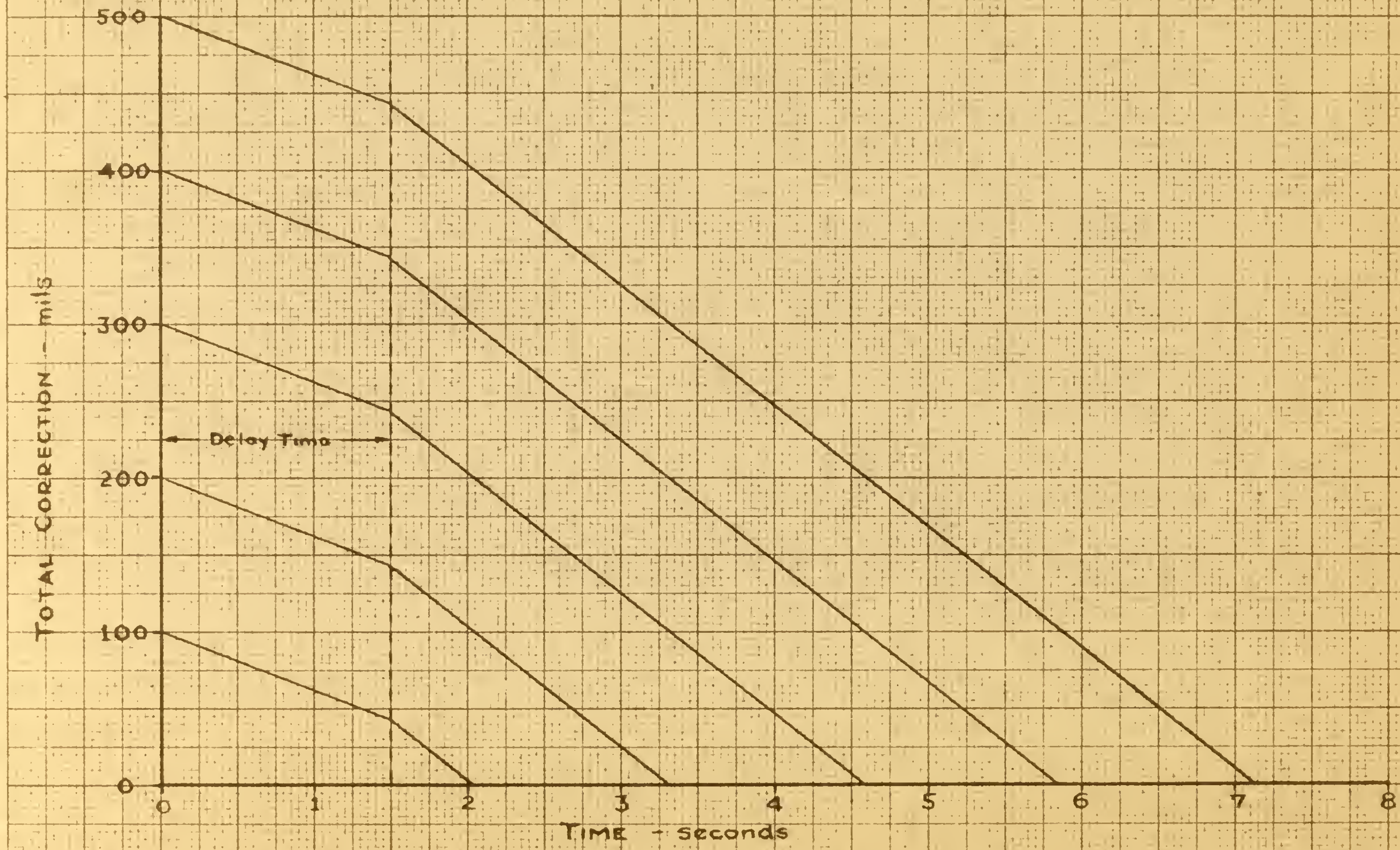

Fig. 20 - Azimuth Total Correction versus Solution Time

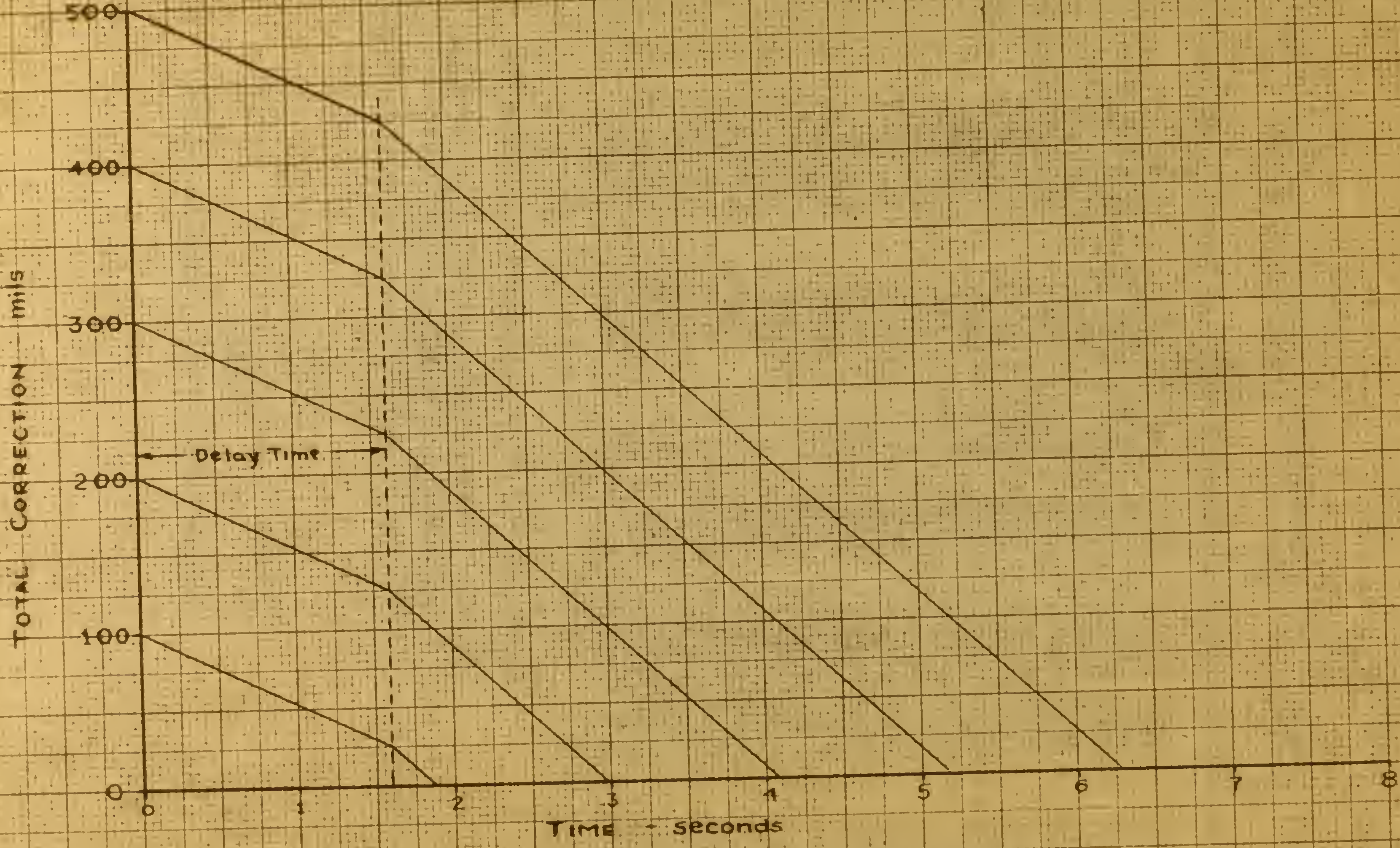

Fig. 21 - Elevation Total Correction versus Solution Time

Input Freq. $\left(\frac{\text{cycles}}{\text{sec}}\right)$	Output $= \theta_o$				Error $\theta_i - \theta_o$		Transfer Function θ_o/E		Amp. Ratio θ_o/θ_i
	mag.	"x"	"z"	$\sin^{-1}\frac{x}{z}$ phase (degrees)	mag.	phase (degrees)	mag.	phase (degrees)	mag.
.147	2.00	0.40	2.00	-11.52	0.40	82.9	5.000	-94.4	1.000
.333	2.00	0.50	2.00	-14.46	0.50	81.7	4.000	-96.2	1.000
.446	2.00	0.60	2.00	-17.45	0.60	80.0	3.330	-97.5	1.000
.675	2.00	0.90	2.00	-26.73	0.90	75.8	2.220	-102.5	1.000
.743	2.19	0.65	2.19	-17.30	0.66	97.0	3.320	-114.3	1.095
.783	2.20	0.50	1.22	-24.20	0.88	90.0	2.500	-114.2	1.100
.816	2.23	0.55	1.22	-26.80	0.99	90.0	2.250	-116.8	1.115
.990	2.40	0.80	1.20	-42.00	1.61	82.0	1.490	-124.0	1.200
1.000	2.25	0.75	2.25	-19.50	0.77	101.0	2.920	-120.5	1.125
1.050	2.10	1.70	2.10	-54.10	1.85	65.5	1.135	-119.6	1.050
1.050	2.00	1.40	2.00	-44.50	1.50	67.0	1.332	-111.5	1.000
1.065	1.95	1.55	1.95	-52.50	1.75	62.0	1.113	-114.5	0.975
1.175	1.64	1.50	1.64	-66.50	2.03	48.6	0.808	-115.1	0.820
1.230	1.80	1.70	1.80	-70.90	2.22	50.0	0.811	-120.9	0.900
1.300	1.37	+1.37	1.37	-90.00	2.43	35.0	0.564	-125.0	0.685
1.610	1.00	-0.90	1.00	-115.80	2.61	20.0	0.383	-135.8	0.500
1.890	0.80	-0.70	+0.80	-118.90	2.50	+16.0	0.320	-134.9	0.400
2.220	0.60	-1.70	-1.90	-243.60	2.35	-13.8	0.255	-229.8	0.300
2.440	0.50	-1.80	-1.90	-251.30	2.20	-12.5	0.227	-238.8	0.250
2.860	0.35	-2.00	-2.10	-252.30	2.14	- 9.5	0.164	-242.8	0.175
3.220	0.30	+1.80	-2.00	-295.80	1.88	- 3.8	0.159	-292.0	0.150
3.700	0.35	1.80	-2.60	-316.20	1.76	- 3.6	0.199	-312.6	0.175

Zero position of input, θ_i, set at 375 yards range.

Amplitude of θ_i for sinusoidal variation = 25 yards (equivalent to 2.00 units magnitude).

TABLE I

Frequency Analysis Data for Range Channel.

Time to close range 800 yds. (seconds)	Range-Rate (yds/sec)	Range-Rate (miles/hr)	Error defl.of CRO (10^{-1} inch)	Error (volts)
21.6	37.0	75.6	9.0	0.450
22.2	36.0	73.6	9.5	0.475
17.6	45.5	93.0	9.5	0.475
17.3	46.3	94.8	10.0	0.500
14.7	54.4	111.2	10.0	0.500
14.4	55.6	113.8	10.0	0.500
11.6	69.0	141.0	11.0	0.550
11.8	67.8	138.6	11.0	0.550
9.9	80.9	165.2	12.0	0.600
9.8	81.6	166.9	11.8	0.590
8.3	96.4	197.0	12.5	0.625
8.3	96.4	197.0	12.5	0.625
7.5	106.7	218.0	12.5	0.625
7.5	106.7	218.0	12.5	0.625
6.3	127.0	259.6	13.5	0.675
6.4	125.0	255.5	14.0	0.700
5.3	151.0	308.7	14.0	0.700
5.3	151.0	308.7	14.0	0.700
4.7	170.1	348.0	14.5	0.725
4.6	173.9	355.5	14.5	0.725
4.2	190.2	389.0	15.5	0.775
4.3	186.0	380.0	15.5	0.775
4.0	200.0	409.0	16.0	0.800
3.8	210.5	431.0	16.5	0.825
3.4	235.0	481.0	17.0	0.850
3.2	250.0	511.0	18.5	0.925
3.0	267.0	546.0	20.0	1.000
2.4	333.0	681.0	22.0	1.100

Data taken for a closing range from 1200 to 400 yards.

Cathode Ray Oscilloscope calibration - 3 inch deflection equivalent to 1.500 volts.

TABLE II.

Data for Velocity Study of Range Channel.

Mean Range (yards)	Range Increment (± yds)	Error (volts)	Sensitivity (yds/volt)	Residual Errors (volts)
275	25	9.75	5.13	.30
325	25	7.35	6.80	.31
375	25	5.33	9.38	.42
425	25	4.75	10.52	.35
475	25	4.10	12.19	.42
525	25	3.80	13.15	.38
575	25	3.05	16.39	.38
625	25	2.97	16.83	.43
683	33	3.60	18.22	.45
758	42	4.15	20.23	.48
850	50	4.40	22.70	.58
950	50	3.75	26.65	.62
1050	50	4.00	25.00	.62
1150	50	3.42	29.25	.65
1250	50	3.05	32.80	.60
1350	50	4.15	24.10	.50
1450	50	4.40	22.70	.45

TABLE III.

Range Sensitivity Data.

Range (yds)	Range-Rate (yds/sec)	Range-Rate (miles/hr)
250	109	223
300	125	256
400	155	317
500	185	378
600	216	442
700	246	504
800	277	566
900	307	628
1000	337	690
1100	368	753
1200	398	815
1300	429	879
1400	459	940
1500	489	1000

TABLE IV.

Maximum Range-Rate Inputs at Various Ranges.

Frequency	X	Z	θ_i/E		θ_o/θ_i	
cycles/sec	CRO units	CRO units	Magnitude	Phase angle (degrees)	Magnitude	Phase angle (degrees)
.205	5	5	4.0	-90.0	1.03	-14
.65	9	9	2.22	-90.0	1.1	-24
.73	10	10	2.0	-90.0	1.115	-26
1.28	17	17.5	1.14	-76.5	1.17	-47
1.39	17	20	1.0	-58.3	1.02	-62
1.90	15.5	32	0.625	-29	.71	-105
2.18	11	29.5	0.722	-22	.63	-117
2.22	10.5	28	0.715	-22	.62	-118
2.42	7.2	25.5	0.785	-16.4	.53	-132
2.54	6.5	29	0.69	-13	.47	-139
2.91	3.5	26.5	0.755	-7.5	.34	-150
3.28	2.75	25	0.80	-6.3	.26	-155
3.52	1.75	24	0.833	-4	.22	-161
3.92	1.5	23	0.87	-4	.18	-172
4.13	1.0	22.5	0.89	-2.5	.15	-178
4.21	0.0	22.5	0.89	0.0	.12	-180
4.65	1.0	22.5	0.89	2.5	.10	-192
5.44	1.0	21.5	0.93	2.75	.097	-212
6.33	1.0	21	0.95	2.75	.063	-243
7.67	0.0	19.0	1.05	0.0	.047	-360

TABLE V.

Frequency Response Study for the Azimuth Channel.

Frequency	X	E	θ_1/E		θ_o/θ_1	
cycles/sec	CRO units	CRO units	Magnitude	Phase angle	Magnitude	Phase angle
.167	5.5	5.5	3.64	-90.0 deg.	1.03	-16.0 deg.
.291	6.6	6.6	3.13	-90.0 "	1.05	-19.0 "
.515	8.5	8.6	2.32	-81.0 "	1.05	-25.5 "
.757	11.1	11.3	1.77	-79.0 "	1.06	-33.0 "
.833	11.5	12.0	1.67	-73.4 "	1.06	-37.0 "
.926	12.5	13.6	1.47	-67.0 "	1.08	-41.0 "
1.06	14.5	15.0	1.33	-75.0 "	1.08	-42.0 "
1.19	16.0	16.8	1.19	-72.0 "	1.09	-44.0 "
1.25	18.4	19.8	1.01	-68.4 "	1.11	-56.0 "
1.47	22.0	27.0	0.74	-54.6 "	1.12	-76.0 "
1.61	19.5	31.0	0.645	-39.0 "	.97	-102.0 "
1.78	15.5	31.5	0.635	-29.5 "	.83	-114.0 "
2.00	15.0	31.0	0.645	-29.0 "	.77	-118.0 "
2.27	8.5	29.0	0.69	-17.0 "	.55	-133.0 "
2.50	7.5	28.0	0.715	-15.5 "	.445	-135.0 "
2.86	4.2	26.0	0.77	-9.3 "	.34	-140.0 "
3.22	2.0	24.0	0.835	-4.8 "	.21	-150.0 "
3.45	2.0	22.0	0.87	-5.0 "	.16	-155.0 "
4.00	1.5	22.0	0.91	-3.9 "	.10	-160.0 "
4.54	1.0	21.0	0.95	-2.7 "	.05	-163.0 "
5.00	1.0	20.5	0.975	-2.8 "	.025	-168.0 "
6.16	0.0	20.5	0.975	0.0 "	.025	-180.0 "

TABLE VI.

Frequency Response Study for the Elevation Channel.

Angular Rate	Error		
Mils/sec	Deflection on CRO - inches	degrees	mils
87	.35	.31	5.41
189	.70	.76	13.28
351	.95	1.06	18.50
507	1.3	1.5	26.2
531	1.5	1.77	30.9
631	1.7	2.02	35.3
719	1.85	2.22	38.8
820	2.1	2.51	43.9

TABLE VII.

Steady State Error for Constant Angular Rotation.

Error	Deflection on CRO
degrees	inches
.17	.25
.34	.35
.51	.50
.68	.60
.85	.80
1.02	.90
1.19	1.00
1.36	1.20
1.53	1.30
1.70	1.50
3.40	2.80

TABLE VIII.

Calibration Table for Cathode Ray Oscilloscope.

	Elevation Channel	Azimuth Channel
Delay Time	1.6 sec.	1.5 sec.
Low Speed Sensitivity	46.5 mils/sec	38.8 mils/sec
High Speed Sensitivity	90.9 mils/sec	78.4 mils/sec

TABLE IX.

TOTAL CORRECTION COMPUTATION DATA.

DATE DUE

7908
Thesis
Y3
Yates
Performance analysis of certain components of fire-control equipment for bombing aircraft.

Thesis
Y3
7908
Yates
Performance analysis of certain components of fire-control equipment for bombing aircraft.

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